2023/07/19

9:30-10:00

Moonshot Goal 6: International Symposium 2023

Progress reports on
Development of Integration Technologies for Superconducting Quantum Circuits

Secure System Platform Research Laboratories

NEC Corporation

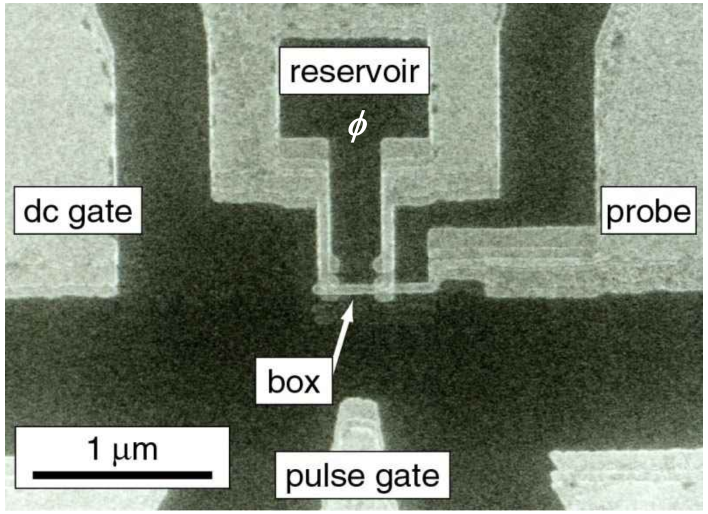
Tsuyoshi Yamamoto

https://ms-iscqc.jp/en/

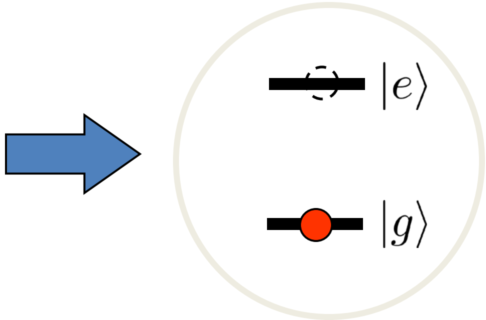
Table of contents

Superconducting qubit

- electric circuit made of superconductor and Josephson junctions
- nonlinear oscillator with ~5 GHz resonance frequency
- operated at ~10 mK using a dilution refrigerator
- lithographically fabricated (⇔ decoherence)
- design flexibility (⇔ non uniformity)



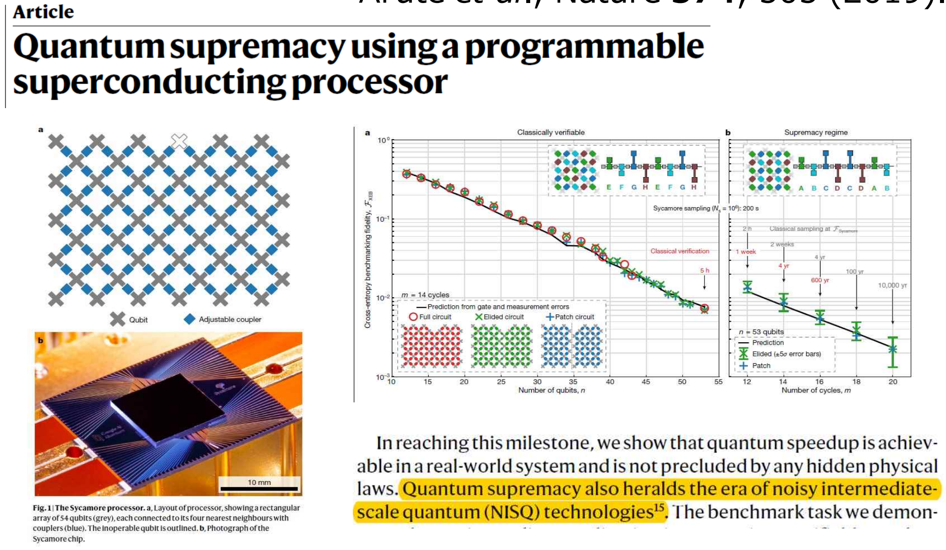
Y. Nakamura et al., Nature **398**, 786 (1999).



Superconducting NISQ processors

Google

Arute *et al.*, Nature **574**, 505 (2019).

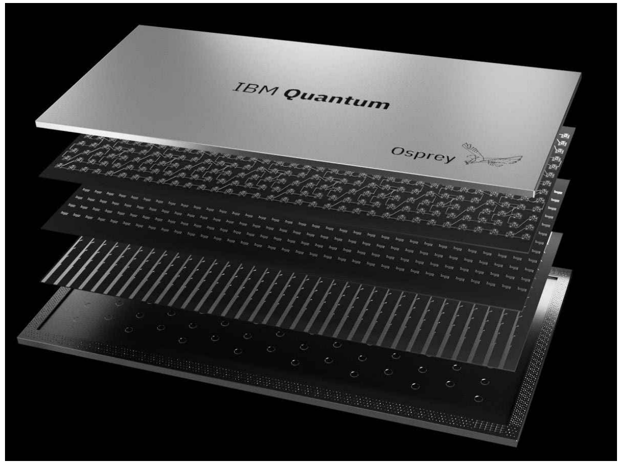

Article

Quantum supremacy using a programmable superconducting processor

Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. b, Photograph of the Sycamore chip.

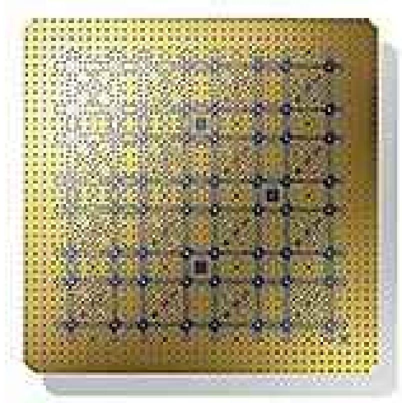
In reaching this milestone, we show that quantum speedup is achievable in a real-world system and is not precluded by any hidden physical laws. Quantum supremacy also heralds the era of noisy intermediate-scale quantum (NISQ) technologies[15]. The benchmark task we demon-

IBM, 433 qubits



[IBM Unveils 433-Qubit Osprey Chip - IEEE Spectrum]

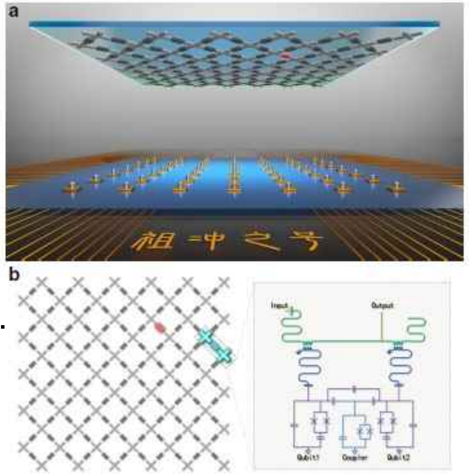
RIKEN RQC, 64 qubits



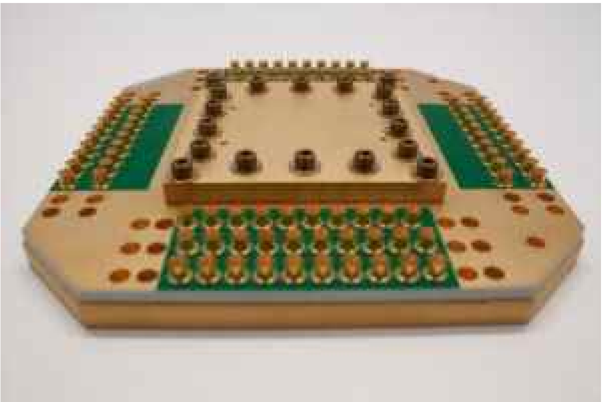
[理化学研究所 量子コンピュータ研究センターセンター長 中村泰信氏 | 電子デバイス産業新聞（旧半導体産業新聞） (sangyo-times.jp)]

USTC, 66 qubits

Zhu et al.,
Science Bulletin **67**, 240 (2022).



Rigetti, 80 qubits

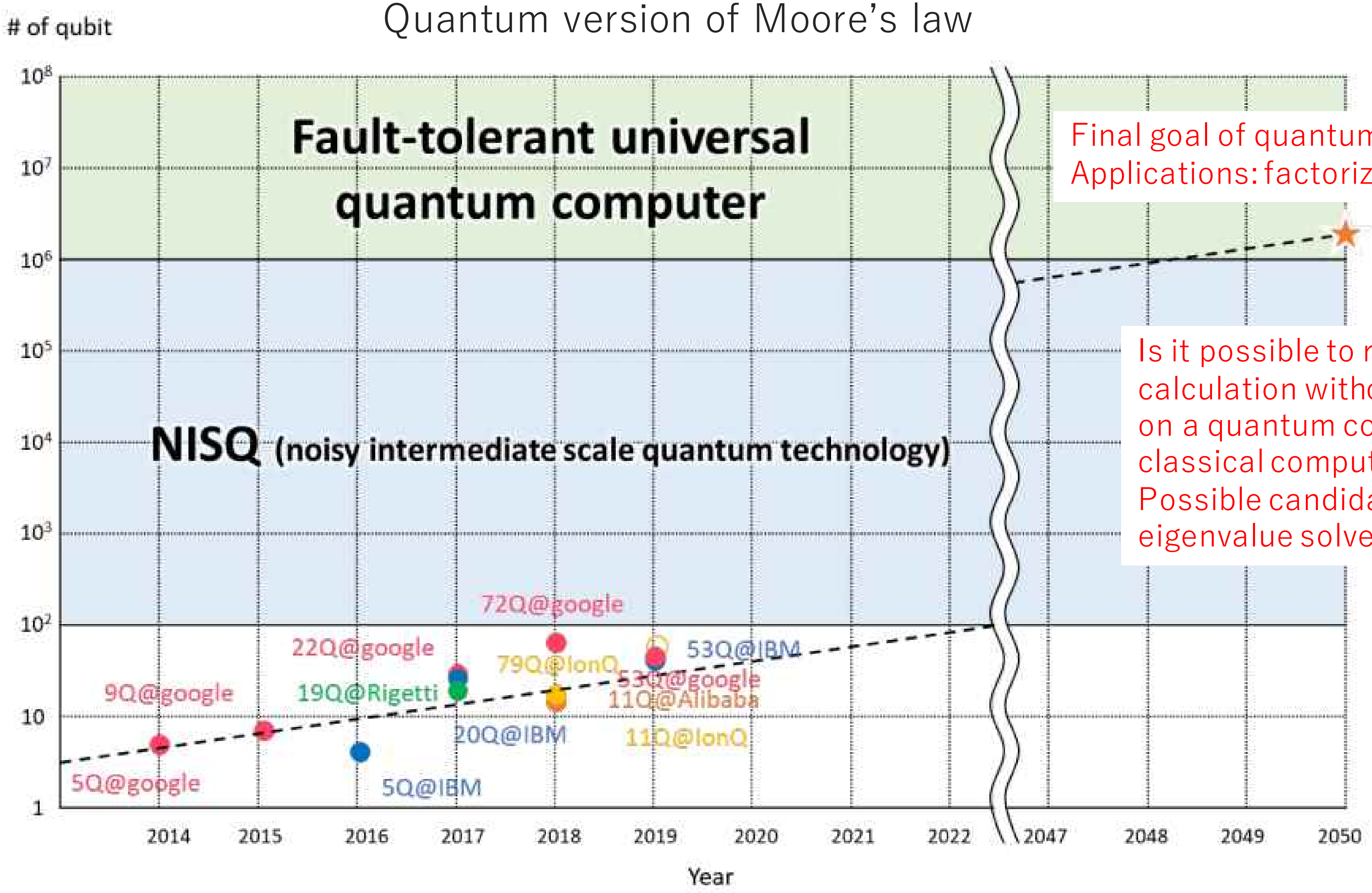


[Rigetti Announces Commercial Availability of Aspen-M System and Results of CLOPS Speed Tests (hpcwire.com)]

\Orchestrating a brighter world NEC

beyond NISQ

Quantum version of Moore's law



Final goal of quantum computer R&D.
Applications: factorization, simulation, etc

Is it possible to run some useful calculation without error correction on a quantum computer faster than classical computer?
Possible candidates: optimization, eigenvalue solver, machine learning

https://www8.cao.go.jp/cstp/english/moonshot/concept6_en.pdf

Toward realization of fault-tolerant QC

◆ Two main problems in hardware development:

■ required large number of physical qubits

Physical qubit error rate	10^{-3}	10^{-6}	10^{-9}
Physical qubits per logical qubit	15,313	1,103	313
Total physical qubits in processor	1.7×10^6	1.1×10^5	3.5×10^4
Number of T state factories	202	68	38
Number of physical qubits per factory	8.7×10^5	1.7×10^4	5.0×10^3
Total number of physical qubits including T state factories	1.8×10^8	1.3×10^6	2.3×10^5

TABLE 3.1 Estimates of the Resource Requirements for Carrying Out Error-Corrected Simulations of a Chemical Structure (FeMoco in Nitrogenase) Using a Serial Algorithmic Approach for Hamiltonian Simulation and the Surface Code for Error Correction

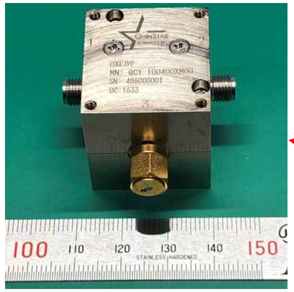
Quantum Computing: Progress and Prospects (2019)

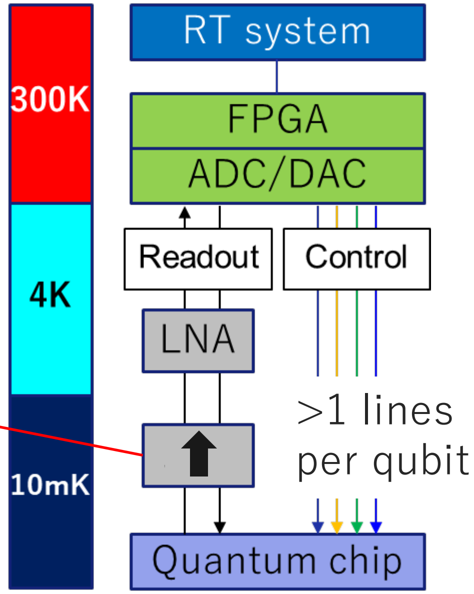
~10^8 qubits?

■ not scalable wiring & electronics

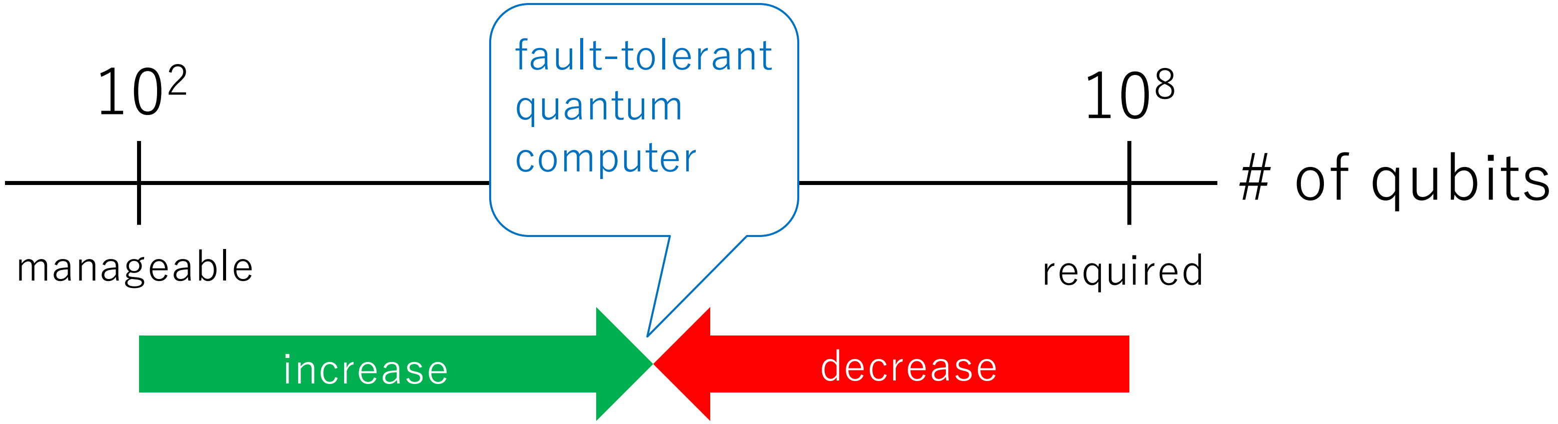
- >1 coax line per qubit from RT to mK for control
- bulky μ-wave components (amplifier, isolator) for readout

<~10^2 qubits?





Required technologies



System-level architecture optimization

- cryo-electronics
- high-cooling-power refrigerator
- high-density wiring
- chip-to-chip interconnection
- …

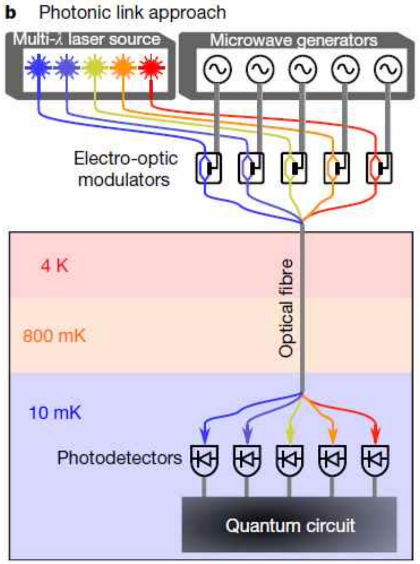
- improved coherence
- gate optimization
- hardware-efficient QEC scheme
- …

Complex scalability trade-offs with huge design-parameter space
e.g. power consumption vs. logical error rate

I. Byun et al., Proceedings of the 49th Annual International Symposium on Computer Architecture, 366 (2022).

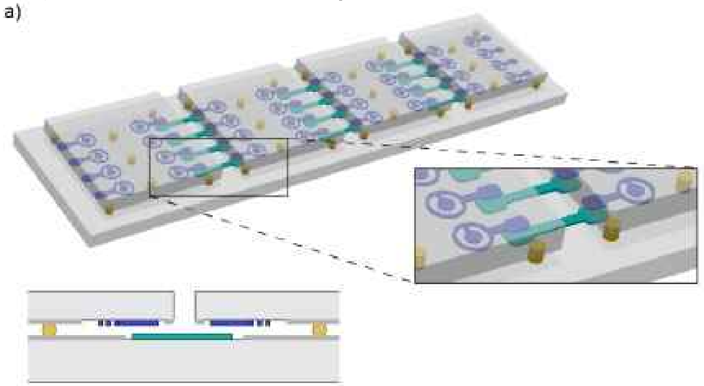
Beyond brute force approach

qubit control via optical fiber (NIST)



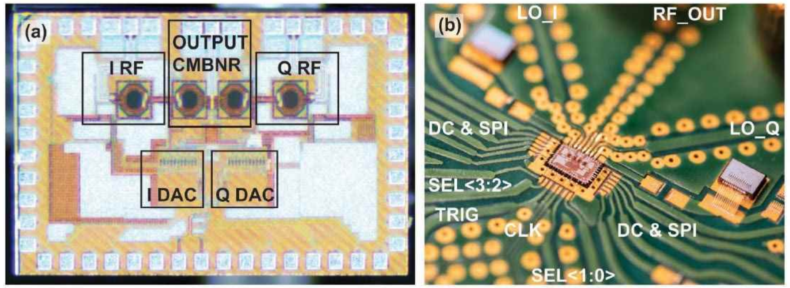
F. Lecocq et al., Nature **591**, 575 (2021).

inter-chip connection (Rigetti)



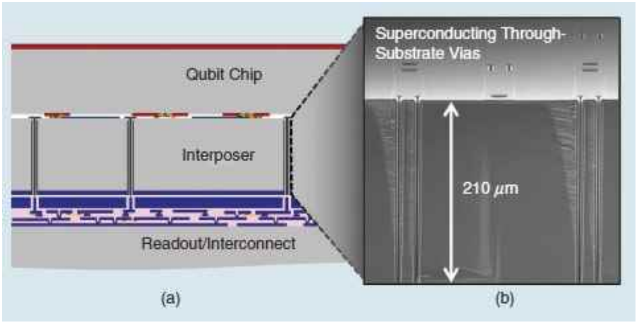
A. Gold et al., NPJ Quant. Inf. **7**, 142 (2021).

cryo-CMOS (Google)



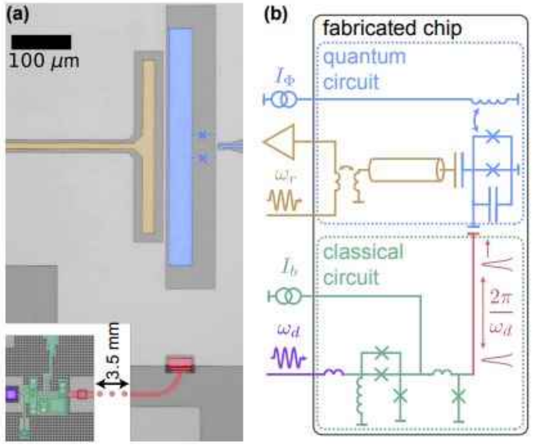
J. C. Bardin et al., IEEE J. Solid-State Circuits **54**, 3043 (2019).

stacked chip structure (MIT)



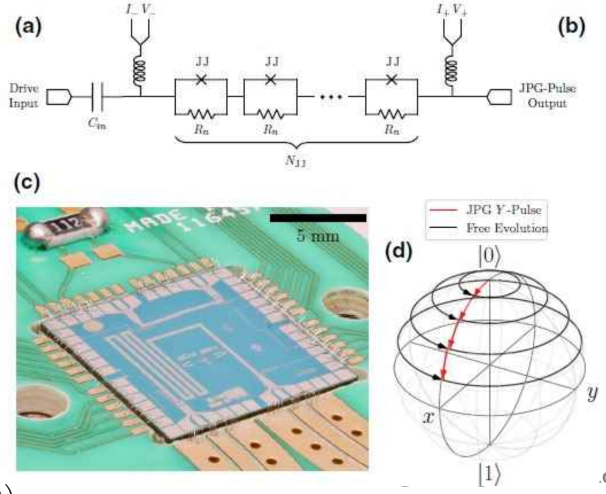
D. Rosenberg et al., IEEE Microw. Mag. **21**, 72 (2020).

qubit control using SFQ pulse (Wisconsin/Syracuse)



E. Leonard Jr. et al., Phys. Rev. Applied **11**, 014009 (2019).

qubit control using Josephson pulse generator (NIST)



L. Howe et al., PRX Quant. **3**, 010350 (2022).

NEC

Architecture for superconducting quantum computer system

On-line quantum error correction using SFQ decoder

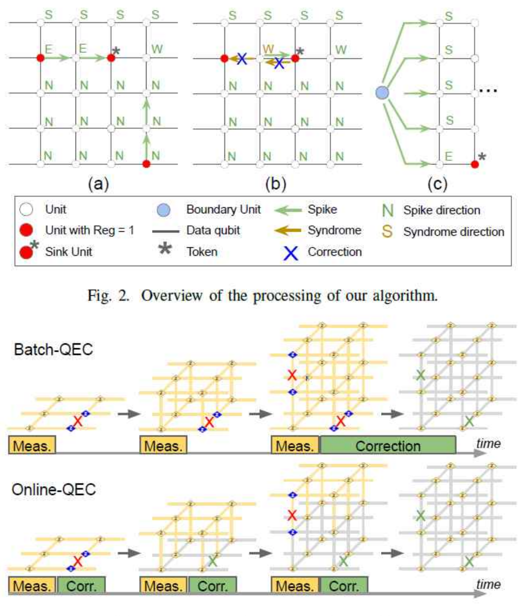


Fig. 2. Overview of the processing of our algorithm.

Fig. 3. Concept of Batch- and Online-QEC

the Univ. of Tokyo
Y. Ueno et al., 2021 58th ACM/IEEE Design Automation Conference (DAC), pp. 451-456

Scalable qubit control system using SFQ circuits

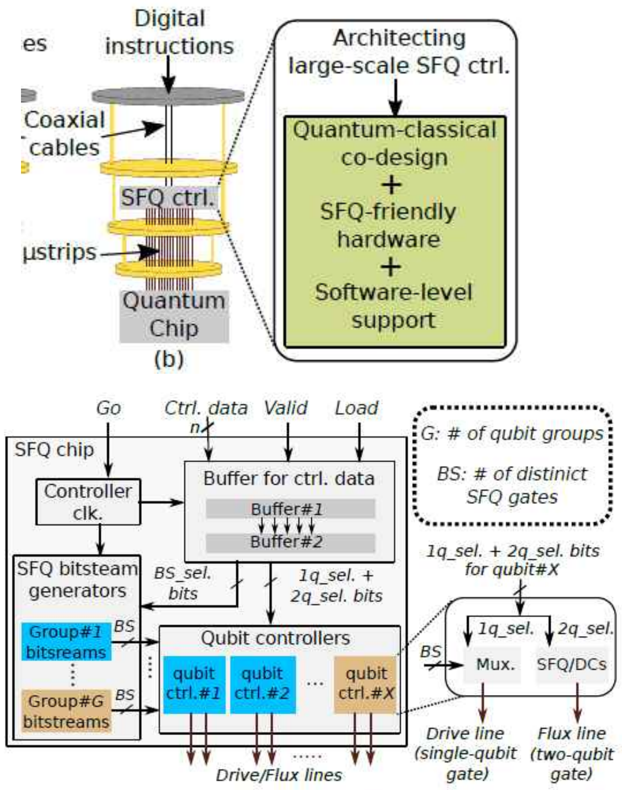
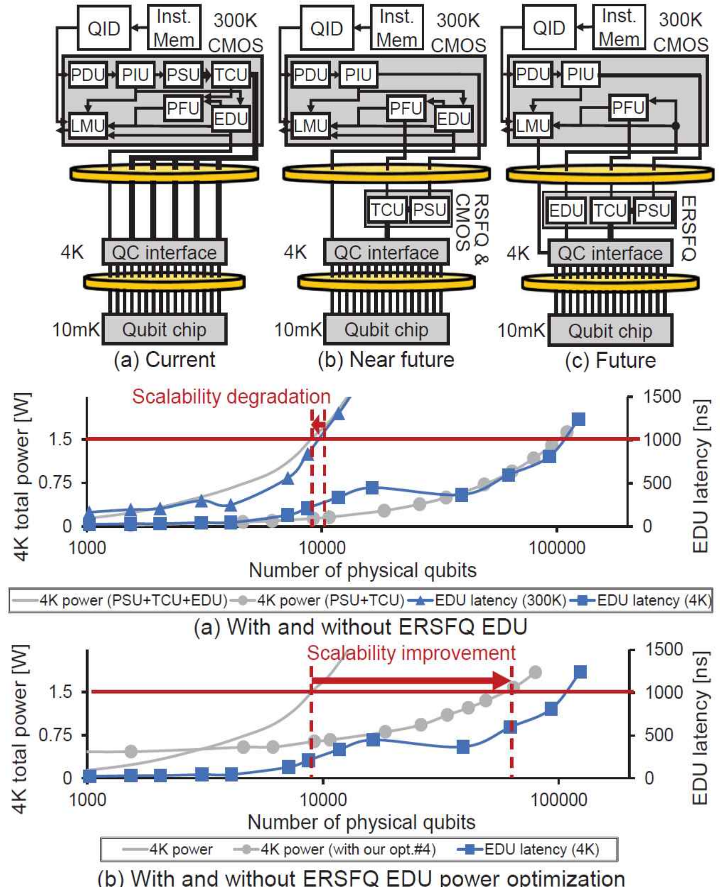


Figure 5: Overview of our DigiQ architecture.

Univ. of Chicago
M. R. Jokar et al., arXiv:2202.01407.

Optimization of error correction micro architecture using Cryo-CMOS and SFQ circuits



Seoul Univ.
I. Byun et al., Proceedings of the 49th Annual International Symposium on Computer Architecture, 366 (2022).

Project teams

6 private companies, 8 universities, 4 national institutes

R&D Target 1: high-quality superconducting qubit for FTQC

qubit decoherence, fabrication with multilayer process, magnetic junctions, bosonic qubits

NEC
AIST
TMDU TOKYO MEDICAL AND DENTAL UNIVERSITY
NICT National Institute of Information and Communications Technology
TOHOKU UNIVERSITY
Nikon
NTT
RIKEN
TOKYO UNIVERSITY OF SCIENCE

R&D Target 2: hardware system for integrated superconducting qubits

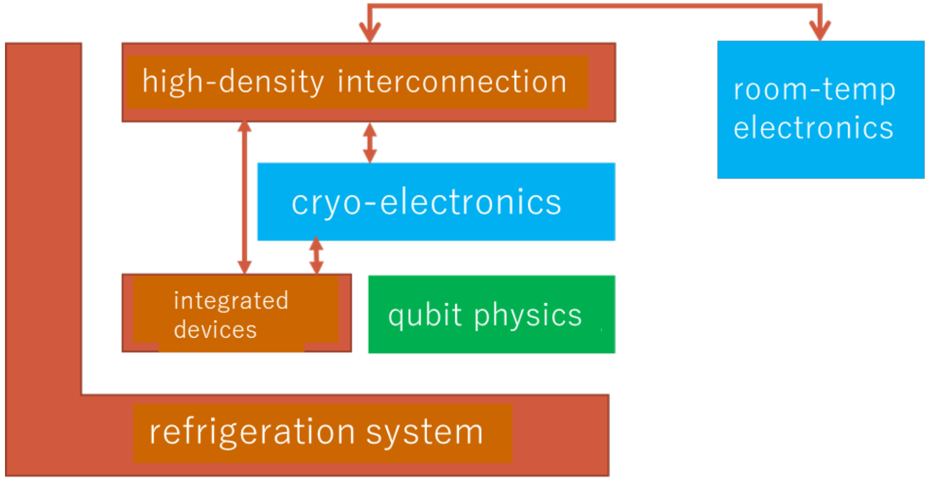
refrigerator, packaging, cryogenic amplifiers

RIKEN
ULVAC
ULVAC CRYOGENICS INC.
国立天文台 NAOJ National Astronomical Observatory of Japan
NICT National Institute of Information and Communications Technology

R&D Target 3: scalable electronics for quantum error correction

RT electronics, cryo-electronics(superconducting flux quantum circuits, cryoFPGA, cryoCMOS), QC architecture

NAGOYA UNIVERSITY
NEC
NBS
大阪大学 OSAKA UNIVERSITY
KYUSHU UNIVERSITY
THE UNIVERSITY OF TOKYO
Keio University



Research themes and PI's

R&D Target 1: high-quality superconducting qubit for FTQC
R&D Target 2: hardware system for integrated superconducting qubits
R&D Target 3: scalable electronics for quantum error correction

K. Inoue

Kyushu Univ : system design for superconducting FTQC

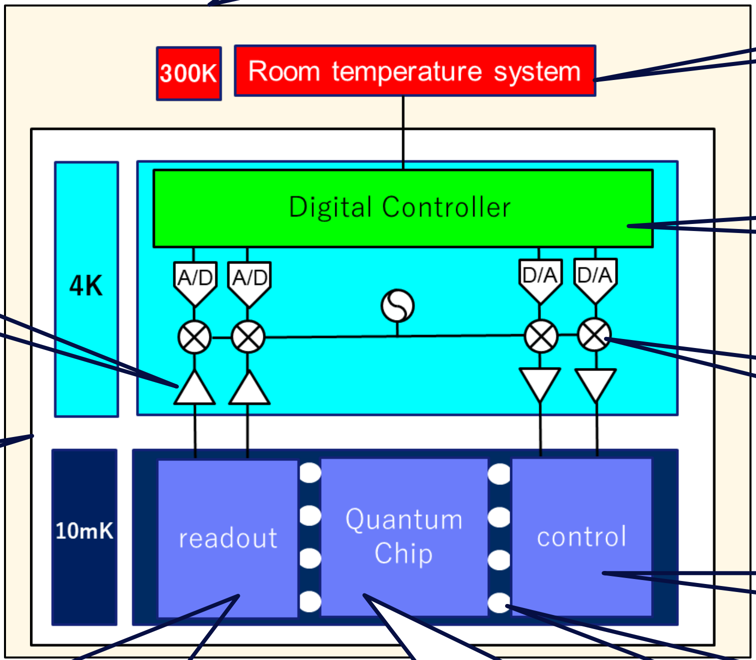
M. Negoro

Osaka Univ. : Scalable Electronics for Quantum Computers

Y. Uzawa

A. Kawakami

NAOJ, NICT: SIS-mixer-based microwave amplifier



M. Tada

K. Uchida

NBS, Univ. of Tokyo : cryo FPGA

M. Saito

Y. Fujiwara

H. Ishikuro

Keio Univ., Univ. of Tokyo: high-frequency analog circuits for low temperature operation

ULVAC, ULVAC Cryogenics : Refrigeration Systems for Quantum Computing

M. Tanaka

T. Yamamoto

Nagoya Univ., NEC: Qubit control using a single flux quantum circuit

K. Koshino

Nagoya Univ., TMDU, RIKEN, NEC: Qubit readout using a single flux quantum circuit

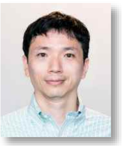
S. Yorozu

RIKEN: Stacked structure of chips with different functions

K. Inomata

S. Odate

F. Yoshihara



T. Yamashita

S. Saito

A. Noguchi

J. S. Tsai

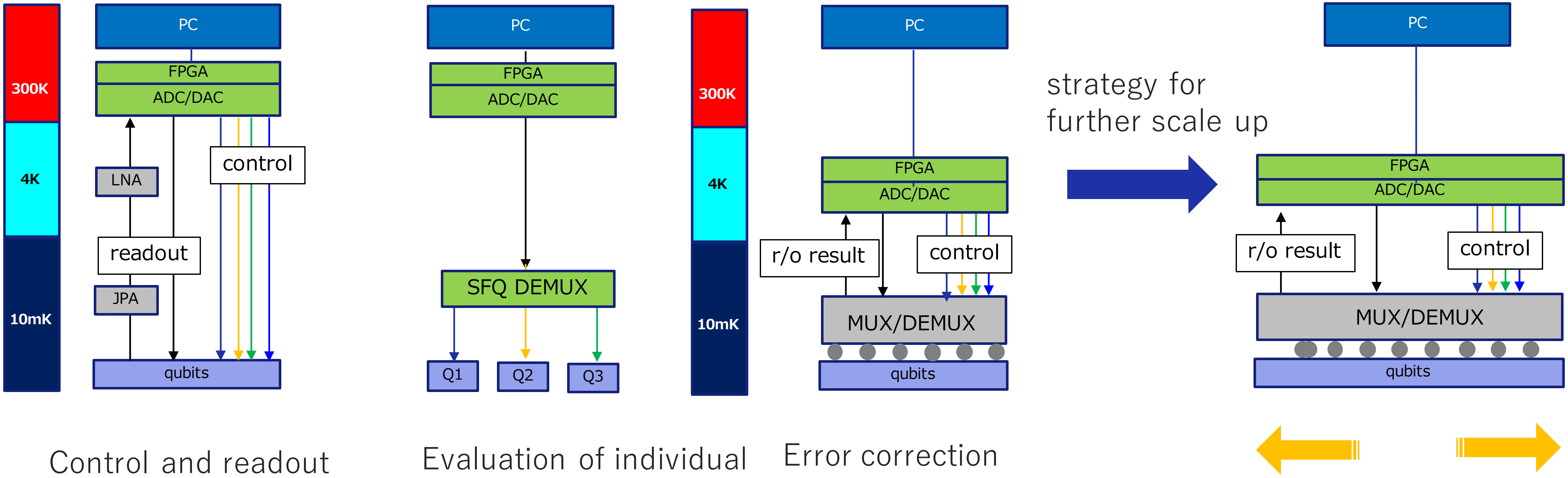
NEC, AIST: Improvement of qubit lifetime and coherence
Tokyo Medical and Dental University: Theoretical study on the qubit readout
NICT, Tohoku Univ.: Qubit with epitaxial junction and magnetic junction
NIKON: Qubit fabrication using CMOS compatible process
NTT, Tokyo University of Science, RIKEN: Bosonic code using superconducting circuits

Goals of the project

start of the project

Goal of current project

2020 2025 2030 2040



Control and readout
with RT electronics
Coax cables > 1/qubit

Evaluation of individual components
e.g.
SFQ demultiplexer (figure),
SIS-mixer based amplifier,
etc

Error correction
with cryo-electronics
Coax cables < 1/qubit

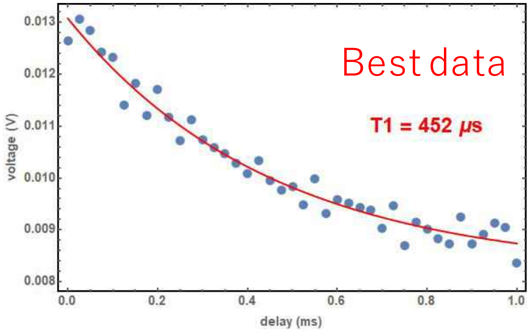
Research progress

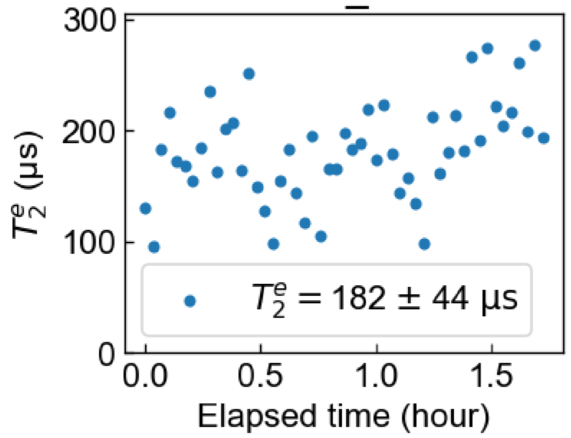
Research highlights (Target 1: high-quality superconducting qubit for FTQC)

details later

RIKEN + NICT teams

High-performance transmon qubits with an epitaxially grown TiN film

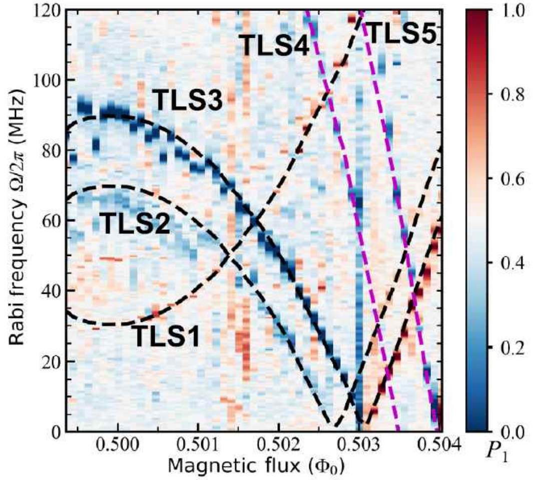




A. Noguchi et al.,
APS March Meeting 2023, M73-5

NTT team

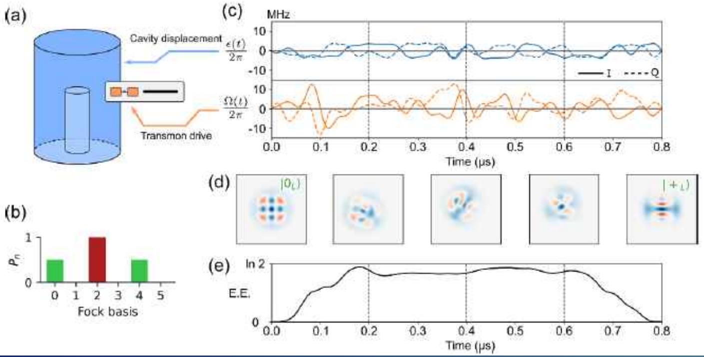
Identification of different types of TLS defects



L. V. Abdurakhimov et al., PRX Quantum **3**, 040332 (2022).

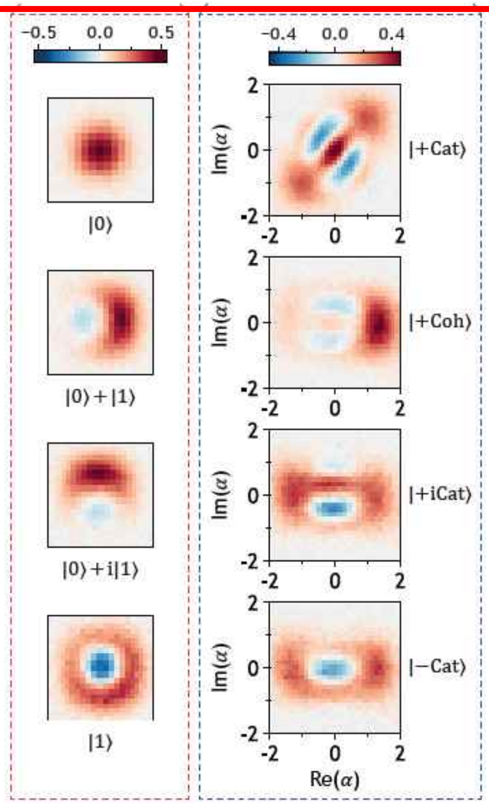
Gate error analysis in SC bosonic qubit

K. Mizuno et al.,
New J. Phys. **25**
(2023) 033007.



Tokyo university of science team

Wigner tomography and gate operations of Kerr cat qubit



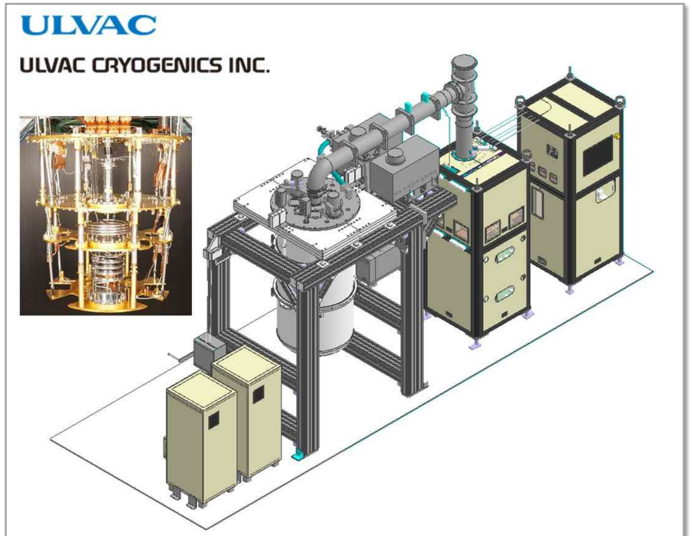
Iyama et al., arXiv:2306.12299.

S. Kwon et al., NPJ Quantum Inf. **8**, 40 (2022).

Research highlights (Target 2: hardware system for integrated superconducting qubits)

details later

Refrigeration system for quantum computing



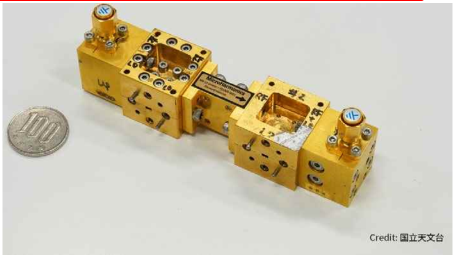
Dry dilution refrigerator system

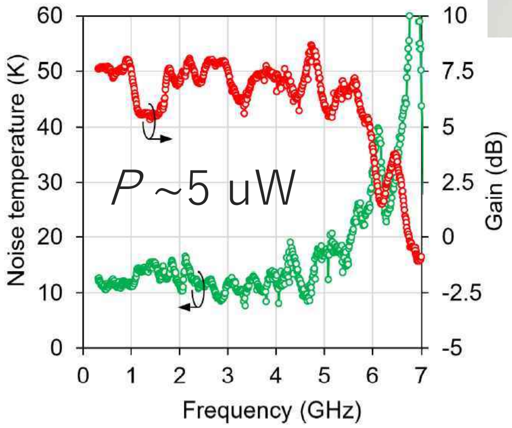
\+

Pulse tube cryocooler system

NAOJ + NICT teams

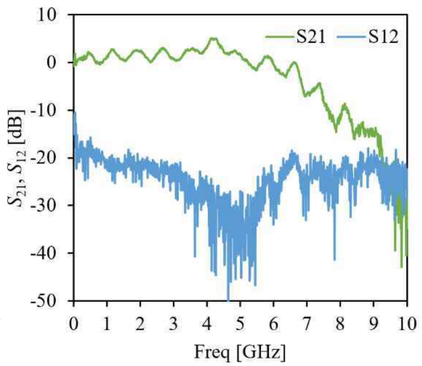
SIS-mixer-based microwave amplifier



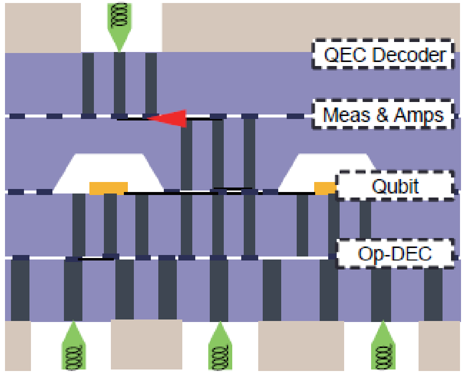


T. Kojima et al.,
Appl. Phys. Lett. **122**, 072601 (2023).

Isolator

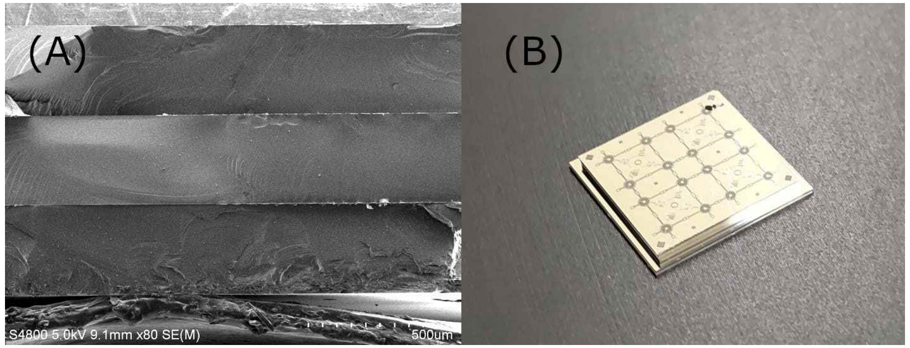


S. Masui et al.,
JSAP meeting 2023 spring



Y. Tabuchi et al.,
2021 Symposium on VLSI Technology, pp. 1-2.

RIKEN team

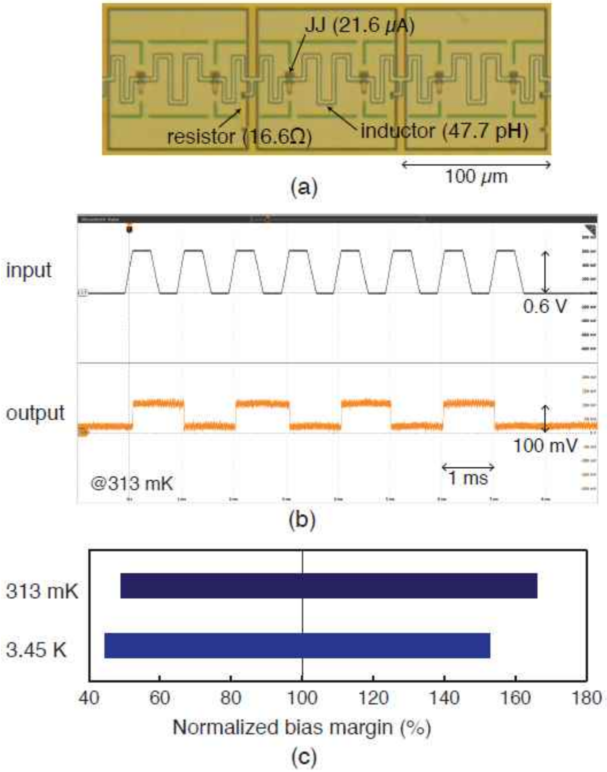


3-tier stack test device
(A) cross-section (B) exterior

Research highlights (Target 3: scalable electronics for quantum error correction)

Nagoya Univ. + NEC teams

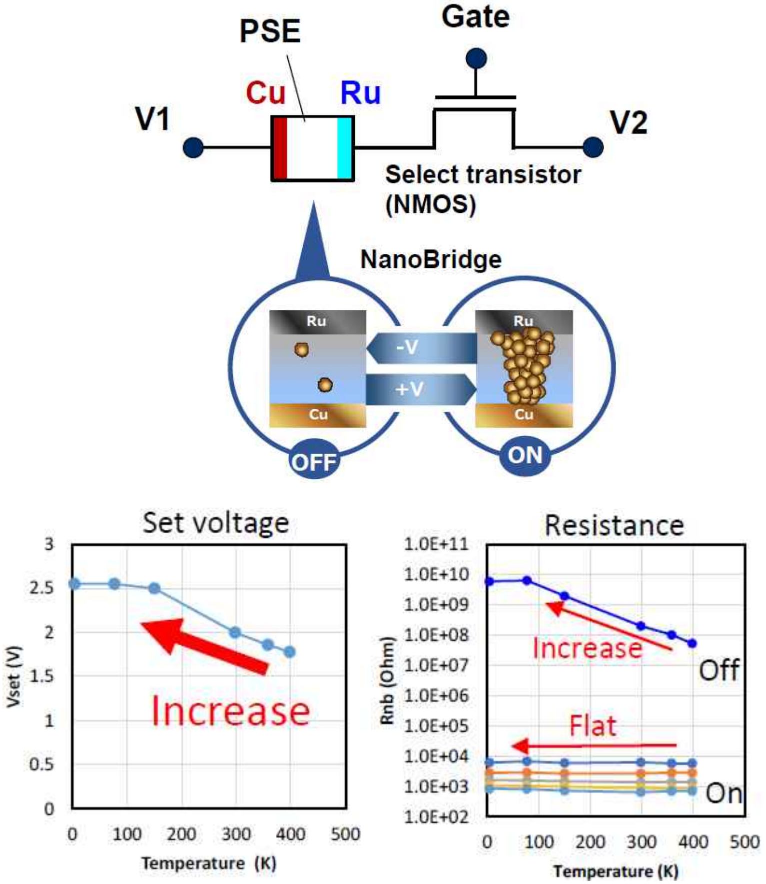
Design and operation of low-power SFQ circuits (j_c=255 A/cm^2, P=7.5 nW/JJ)



M. Tanaka et al.,
IEEE Trans. Appl. Supercond. **33**, 1700805 (2023).

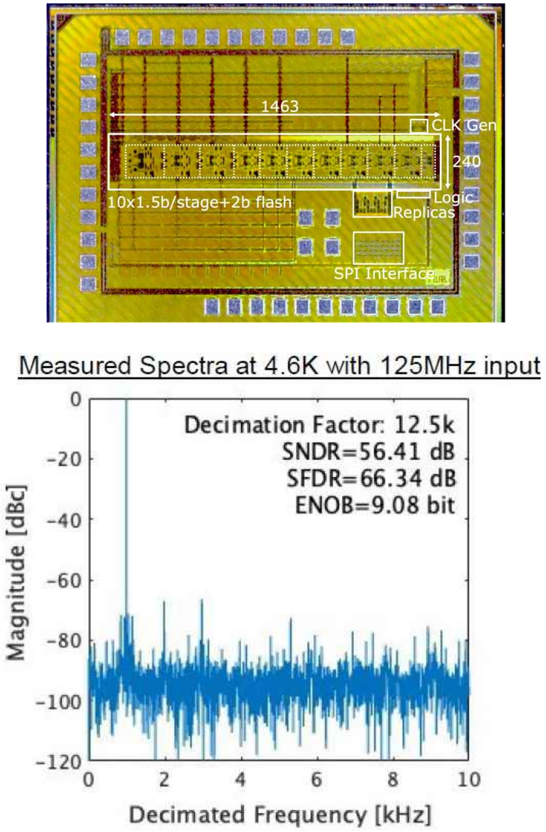
NBS + Keio Univ. + Univ. of Tokyo teams

Cryogenic operation of NanoBridge



K. Okamoto et al.,
Jpn. J. Appl. Phys. **61**, SC1049 (2022).

Cryo-ADC prototype device

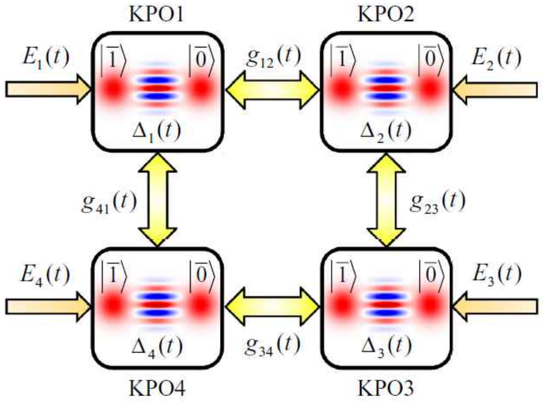


K. Yamashita et al., IEEE Custom Integrated Circuit Conference (CICC 2023).

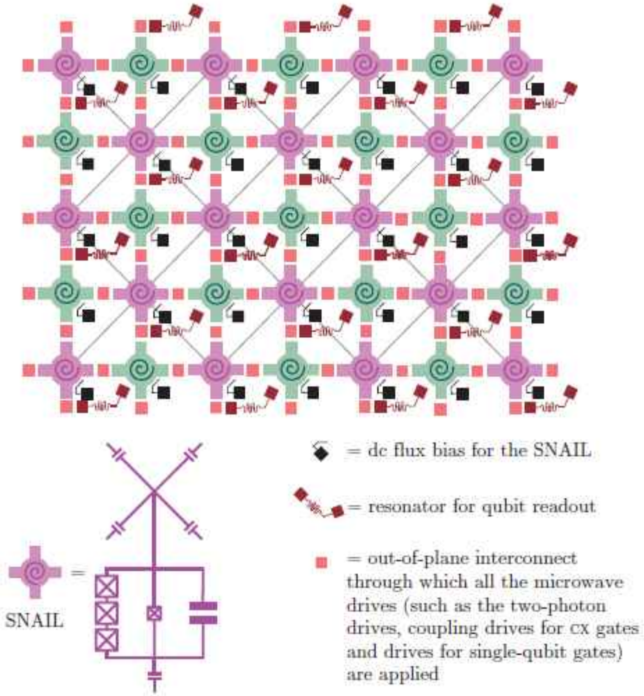
Wigner tomography and gate operations of Kerr cat qubit

Hardware-efficient FTQC using Kerr cat qubit

- Theory of Kerr cat qubit
  - P. T. Cochrane et al., Phys. Rev. A **59**, 2631 (1999).
  - H. Goto, Phys. Rev. A **93**, 050301 (2016).
  - S. Puri et al., npj Quantum Info. **3**, 18 (2017).
- High-fidelity gate operation
  - T. Kanao et al., Phys. Rev. Appl. **18**, 014019 (2022).
  - H. Chono et al., Phys. Rev. Res. **4**, 043054 (2022).
- Proposal of bias preserving gate
  - S. Puri et al., Sci. Adv. 6, eaay5901 (2020).
- Error-correction code with high error threshold
  - A. S. Darmawan et al., PRX Quantum 2, 030345 (2021).
- Experiments
  - Z. Wang et al., Phys. Rev. X **9**, 021049 (2019).
  - A. Grimm et al., Nature **584**, 205 (2020).
  - N. E. Frattini et al., arXiv:2209.03934.
  - J. Venkatraman et al., arXiv:2211.04605.

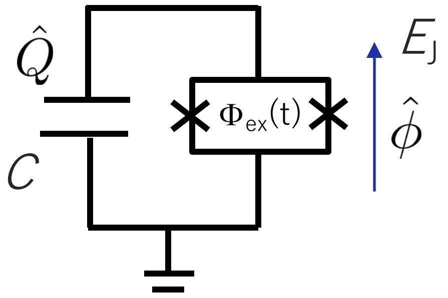


Goto, PRA 2016



Darmawan et al.,
PRX Quantum 2021

Hamiltonian of KPO



$$\mathcal{H}_{\mathrm{KPO}} = \hbar\omega_0\left(a^\dagger a + \frac{1}{2}\right) - \frac{E_c}{12}(a^\dagger + a)^4 + \frac{\hbar\omega_0}{4}\frac{\delta E_J}{E_J}(a^\dagger + a)^2 \cos\omega_p t$$

rotating frame at $\omega_p/2$, and RWA

$$E_J(t) = E_J + \delta E_J \cos\omega_p t$$

$$\hat{\phi} = \left(\frac{2E_c}{E_J}\right)^{1/4}(a^\dagger + a)$$

$$\hat{Q} = \mathrm{i}\left(\frac{E_J}{2E_c}\right)^{1/4}(a^\dagger - a)$$

$$\mathcal{H}_{\mathrm{KPO}}'/\hbar = \Delta a^\dagger a - \frac{K}{2}a^\dagger a^\dagger a a + \frac{\beta}{2}(a^{\dagger 2} + a^2)$$

detuning　Kerr nonlinearity　parametric drive

$$\Delta = \omega_0 - K - \omega_p/2$$

$$K = E_c$$

$$\beta = \frac{\omega_0}{4}\frac{\delta E_J}{E_J}$$

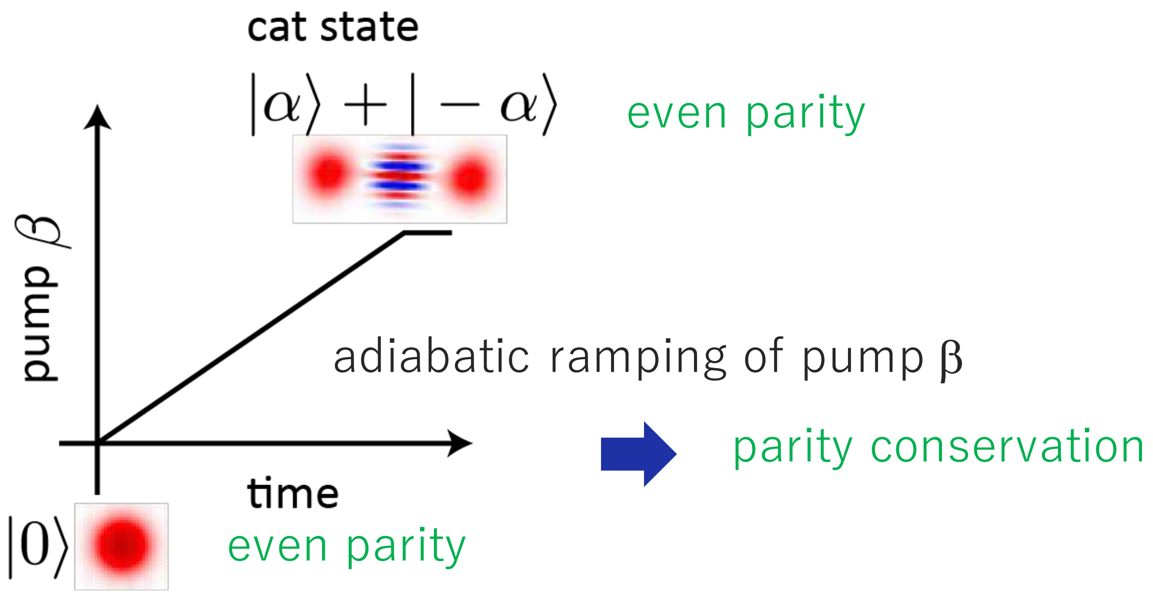
Generation of Schrodinger's cat state

$$\mathcal{H}_{\mathrm{KPO}}/\hbar = -\frac{K}{2}a^\dagger a^\dagger aa + \frac{\beta}{2}({a^\dagger}^2 + a^2)$$
$$= -K\left({a^\dagger}^2 - \frac{\beta}{K}\right)\left(a^2 - \frac{\beta}{K}\right) + \frac{\beta^2}{K}$$

P. T. Cochrane et al., Phys. Rev. A **59**, 2631 (1999).
H. Goto, Sci. Rep. **6**, 21686 (2016).
S. Puri et al., npj Quantum Info. **3**, 18 (2017).

Coherent state is an eigenstate of annihilation operator a, $a|\alpha\rangle = \alpha|\alpha\rangle$

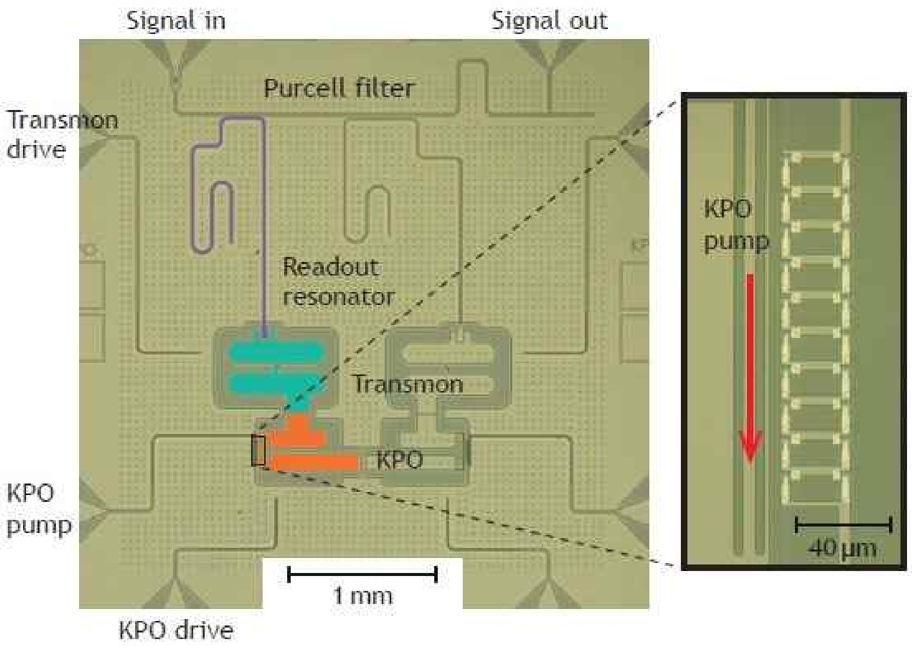
H_{KPO} has degenerate eigenstates of $|\pm\alpha\rangle$, where $\alpha = \sqrt{\frac{\beta}{K}}$



Generation of Kerr cat qubit

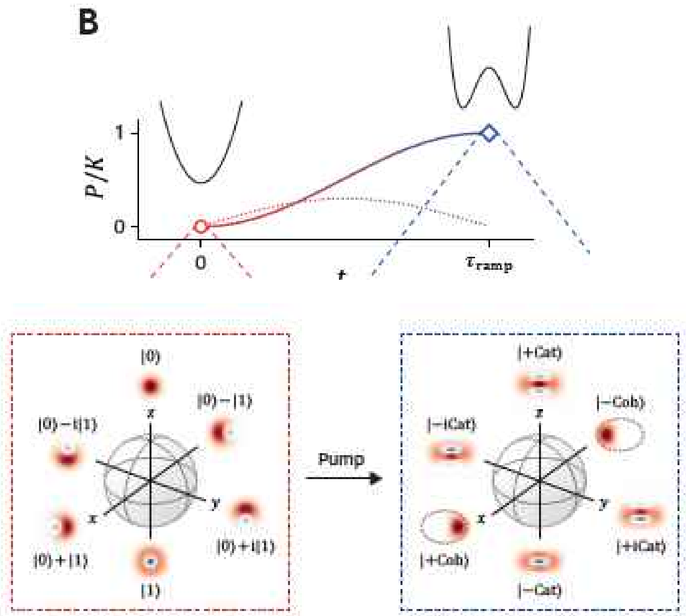
J. S. Tsai

Device picture (coupled KPO device)



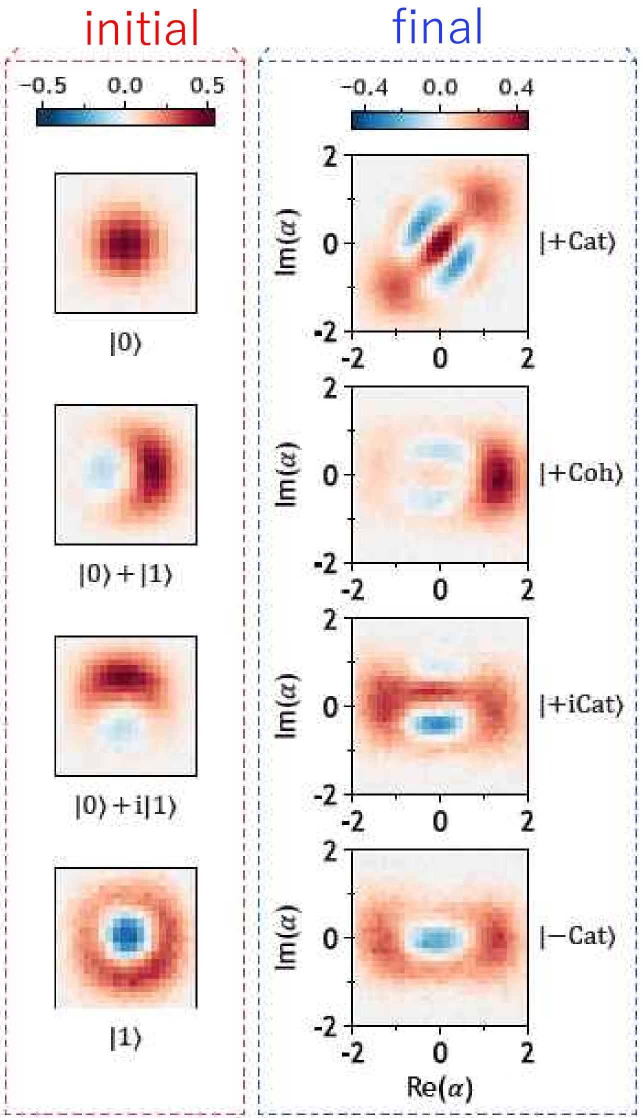
Iyama et al., arXiv:2306.12299.

adiabatic pumping
(with counter diabatic pump)



c.f.
Z. Wang et al., Phys. Rev. X **9**, 021049 (2019).
A. Grimm *et al.*, Nature **584**, 205 (2020).

Wigner tomography

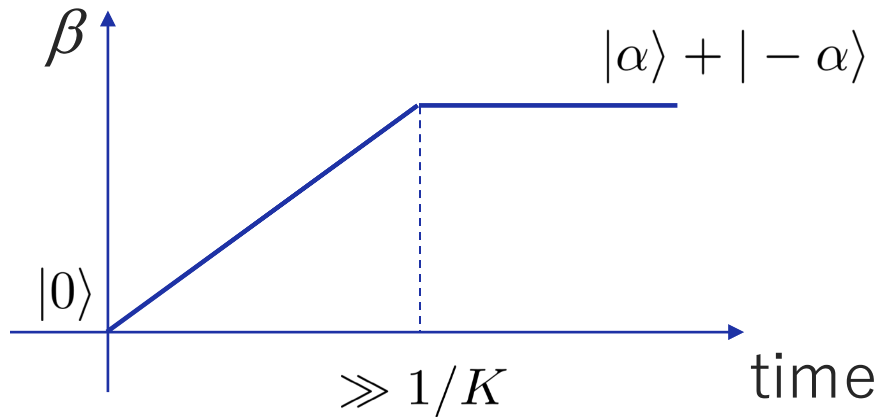


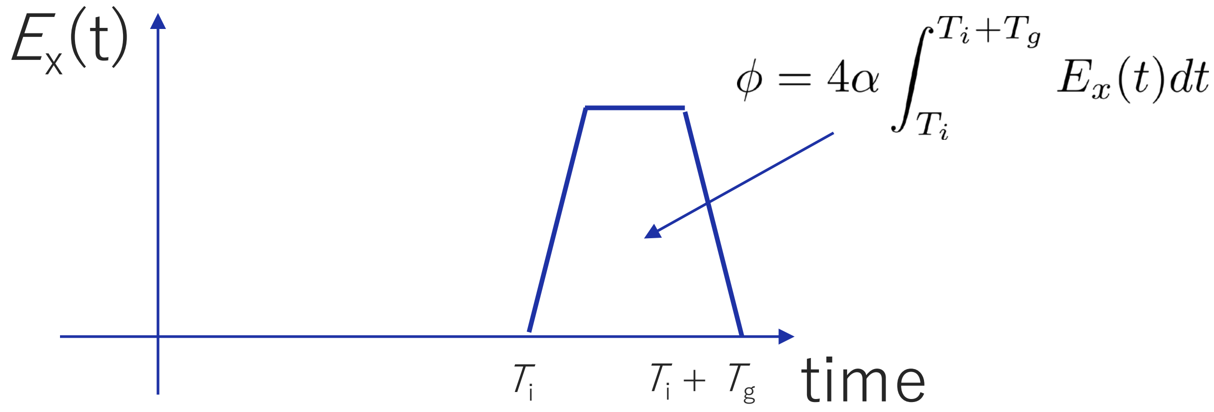
R_x gate

P. T. Cochrane et al., Phys. Rev. A **59**, 2631 (1999).
H. Goto, Sci. Rep. **6**, 21686 (2016).
S. Puri et al., npj Quantum Info. **3**, 18 (2017).

single-photon drive @ $\omega_p/2$

$$\mathcal{H}_{\mathrm{KPO}}/\hbar = -\frac{K}{2}a^\dagger a^\dagger a a + \beta({a^\dagger}^2 + a^2) + E_x(t)(a + a^\dagger)$$





produces energy difference between $|\alpha>$ and $|-\alpha>$

$$\langle\alpha|E_x(t)(a+a^\dagger)|\alpha\rangle = 2\alpha E_x(t)$$

$$\langle-\alpha|E_x(t)(a+a^\dagger)|-\alpha\rangle = -2\alpha E_x(t)$$

in α basis

change to cat basis

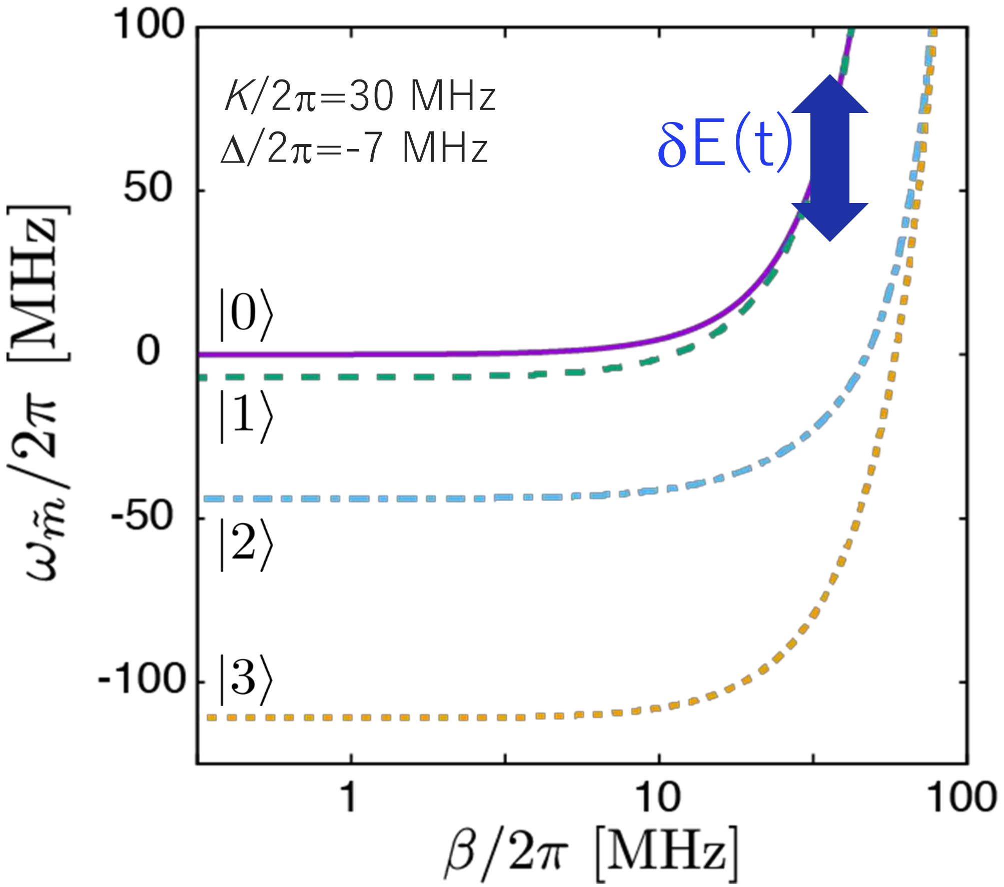
$$H \begin{pmatrix} e^{-i\phi/2} & 0 \\ 0 & e^{i\phi/2} \end{pmatrix} H = \begin{pmatrix} \cos\frac{\phi}{2} & -i\sin\frac{\phi}{2} \\ -i\sin\frac{\phi}{2} & \cos\frac{\phi}{2} \end{pmatrix} = R_x(\phi)$$

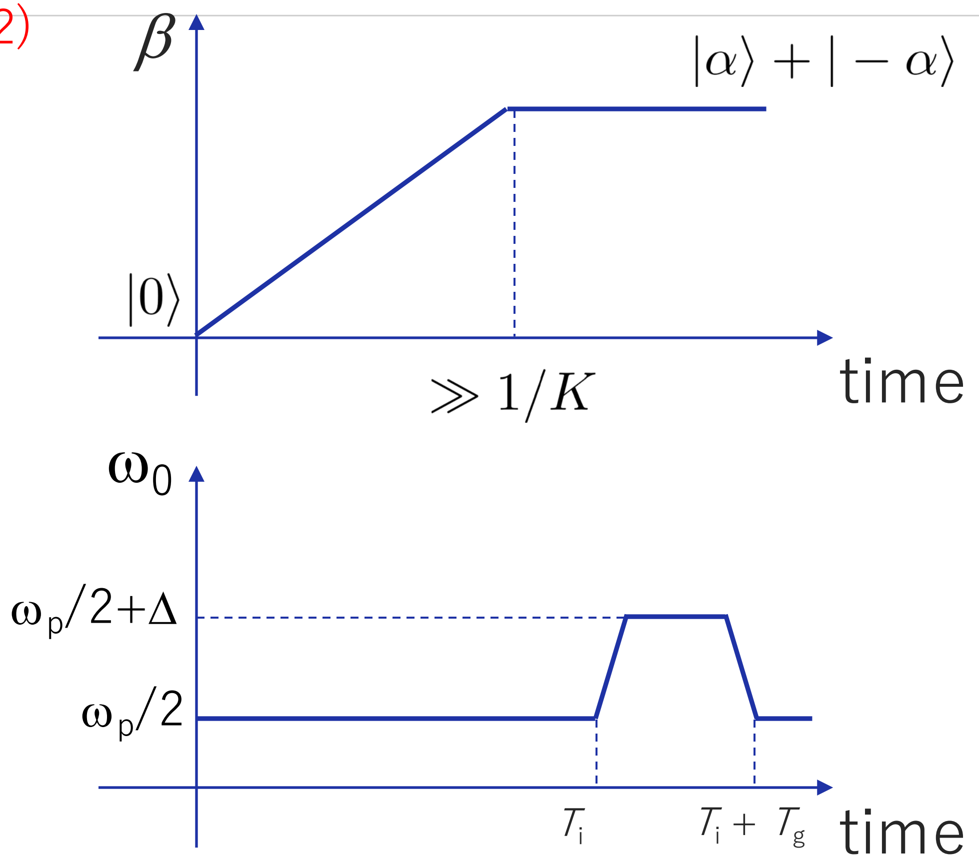
R_z gate

H. Goto, Sci. Rep. **6**, 21686 (2016).
S. Puri et al., npj Quantum Info. **3**, 18 (2017).

detuning (ω_0 - $\omega_p/2$)

$$\mathcal{H}_{\mathrm{KPO}}/\hbar = -\frac{K}{2}a^\dagger a^\dagger a a + \beta(a^{\dagger 2} + a^2) + \Delta(t)a^\dagger a$$





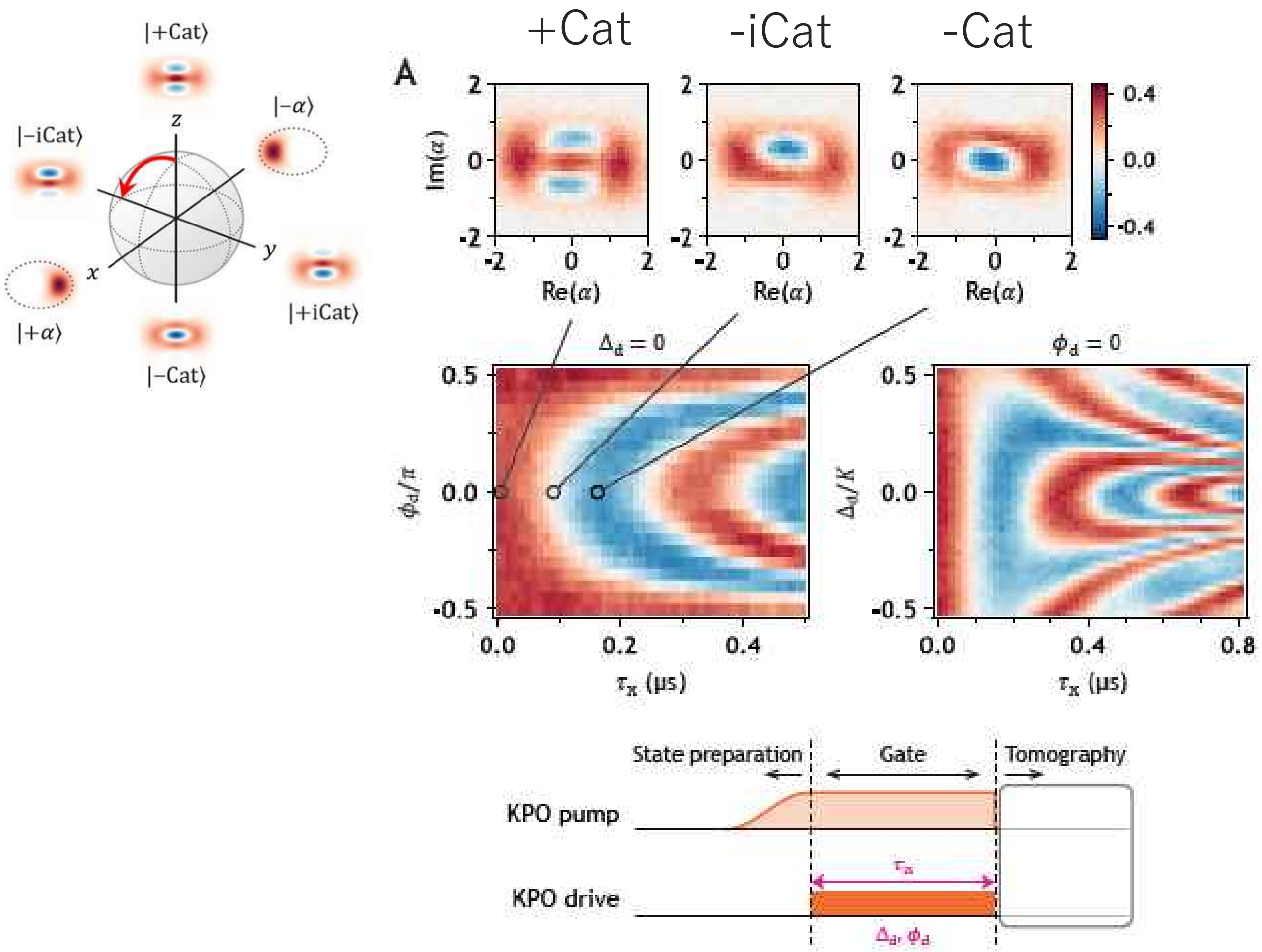
$$\begin{pmatrix} e^{-i\theta/2} & 0 \\ 0 & e^{i\theta/2} \end{pmatrix} \qquad \theta = \int_{T_i}^{T_i+T_g} \delta E(t) dt$$

Alternative method:
temporarily remove the two-photon drive. Grim et al., 2020

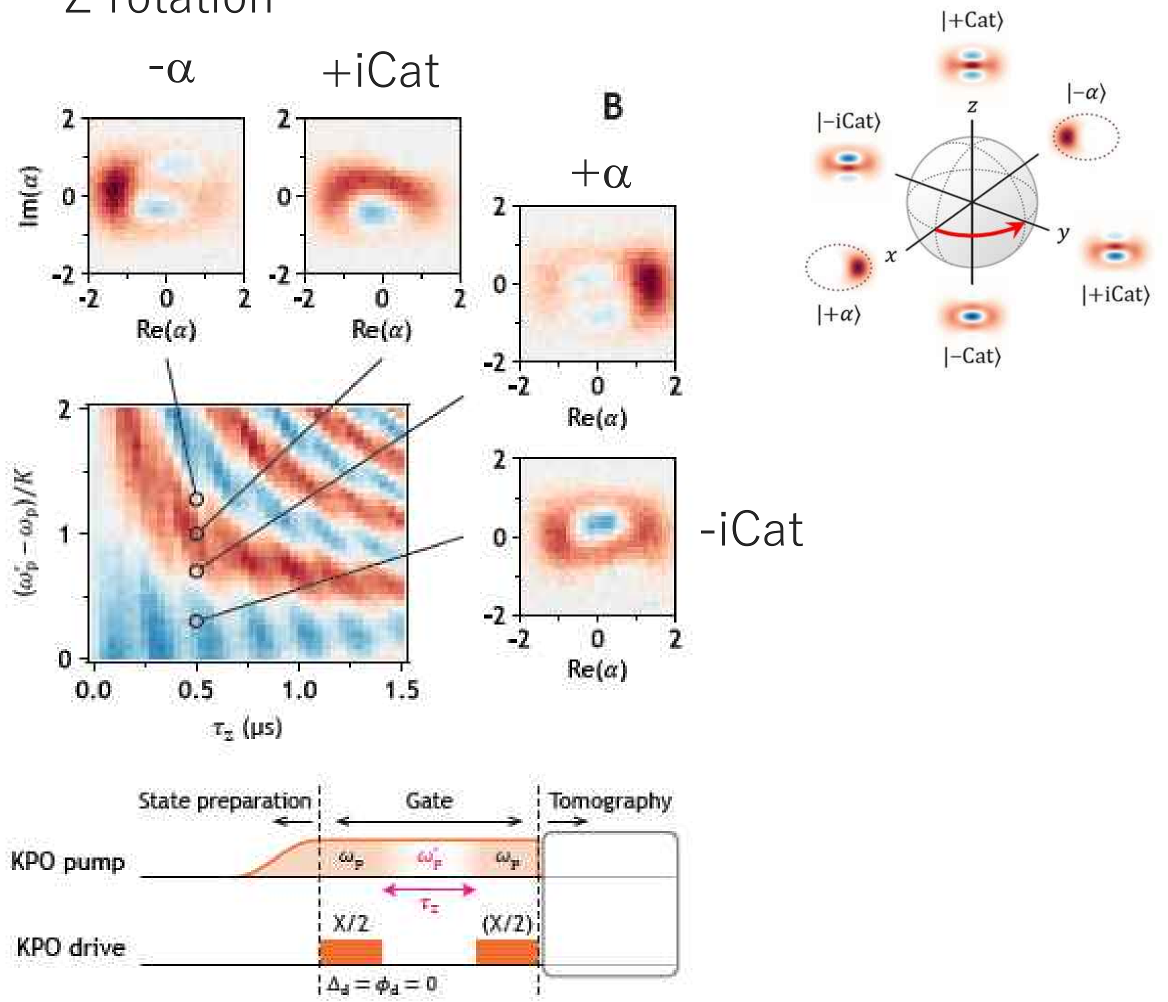
R_x and R_z gate operations

Iyama et al., arXiv:2306.12299.

X rotation



Z rotation

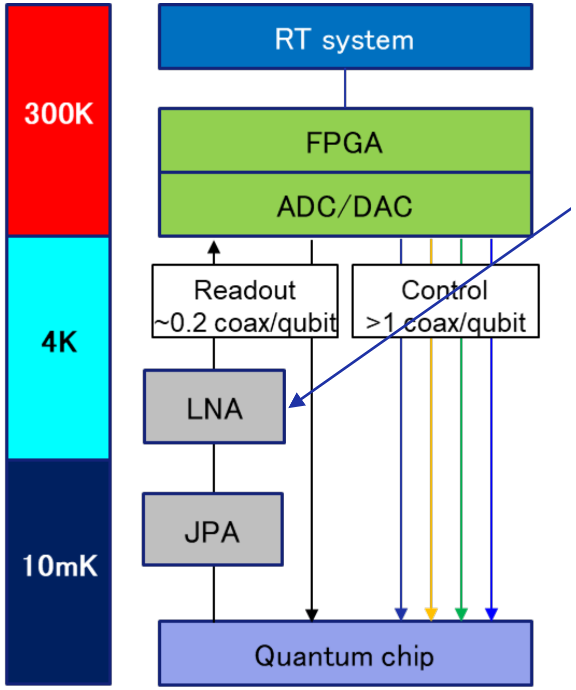


process fidelity for $R_x(\pi/2) = 0.844$

process fidelity for $R_z(\pi/2) = 0.794$

SIS-mixer-based microwave amplifier

Low-noise microwave amplifier for qubit readout



Datasheet

LNF-LNC4_8F

4-8 GHz Cryogenic Low Noise Amplifier

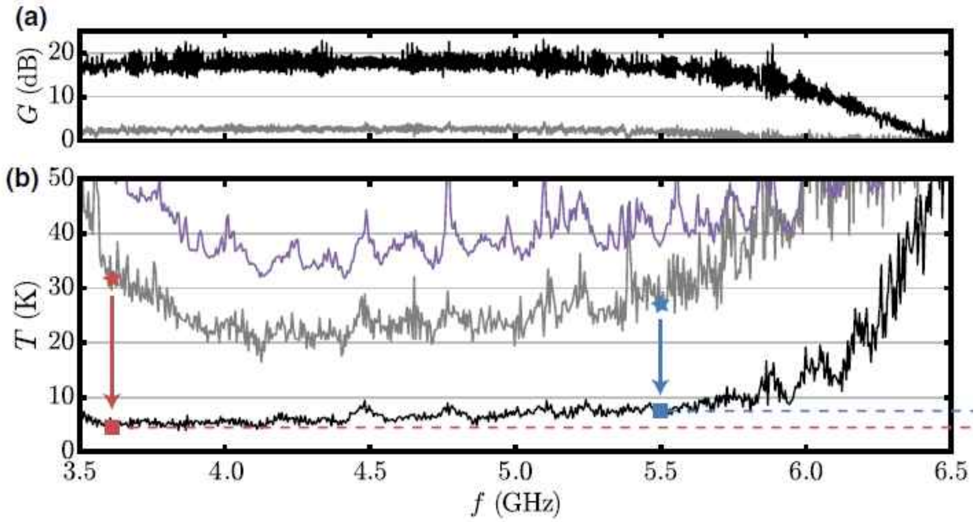
Product Features	
RF Bandwidth	4-8 GHz
Noise Temperature	1.5 K
Noise Figure	0.022 dB
Gain	44 dB
DC power (typical)	V_{ds} = 0.6 V, I_{ds} = 13 mA*
RF Connectors	Female SMA**
DC Connectors	9-pin Female Nano-D
One gate and one drain supply only	

P ~10 mW
~1% of cooling power

PHYSICAL REVIEW APPLIED **17**, 044009 (2022)

Performance of a Kinetic Inductance Traveling-Wave Parametric Amplifier at 4 Kelvin: Toward an Alternative to Semiconductor Amplifiers

M. Malnou,[1,2,*] J. Aumentado,[1] M.R. Vissers,[1] J.D. Wheeler,[1] J. Hubmayr,[1] J.N. Ullom,[1,2] and J. Gao[1,2]

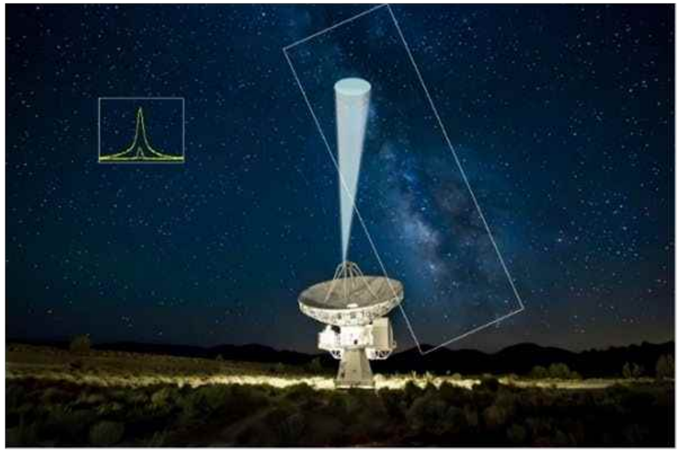


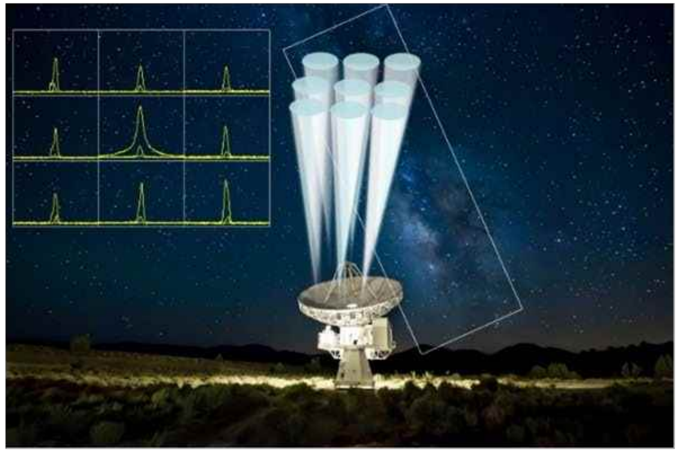
NIST
Gain ~18 dB
Noise temperature ~1.9 K
P ~ 100 uW
(RF driven)

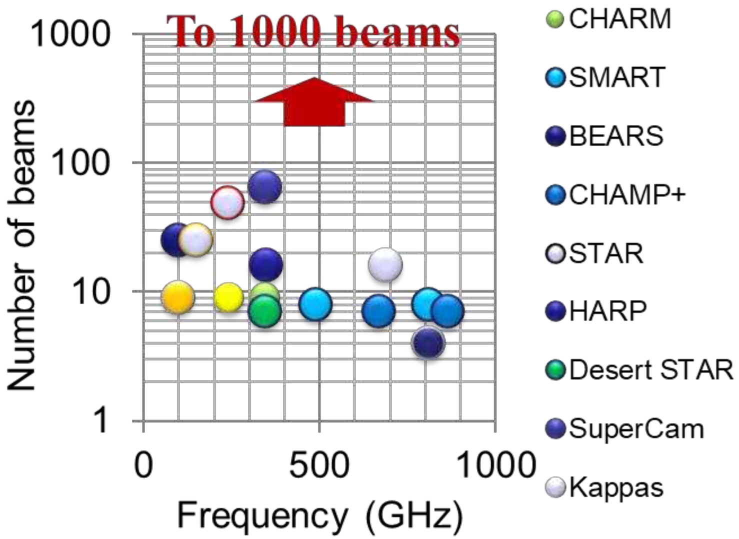
Scalability problem in radio astronomy

slide courtesy, Y. Uzawa

- Superconducting receivers in telescopes go from single-beam to multi-beam

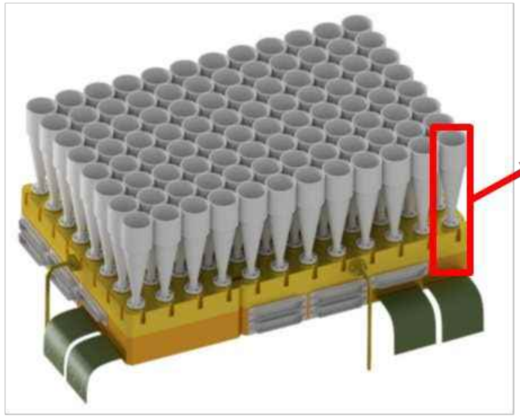


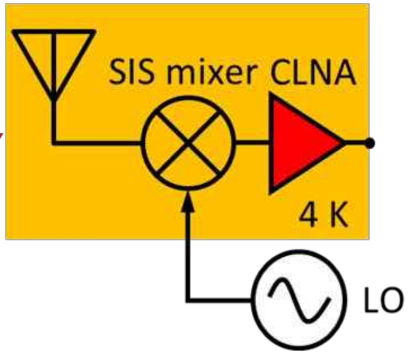




Observation efficiency proportional to the number of beams

- Challenges in scaling up multibeam receivers





Challenge 1

Make compact of receiver frontend

=> integrated superconducting circuit

Challenge 2

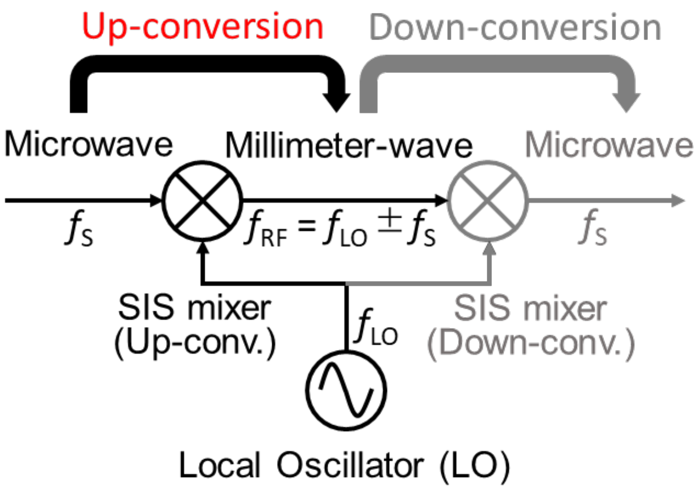
Reduction of power consumption at the 4K stage

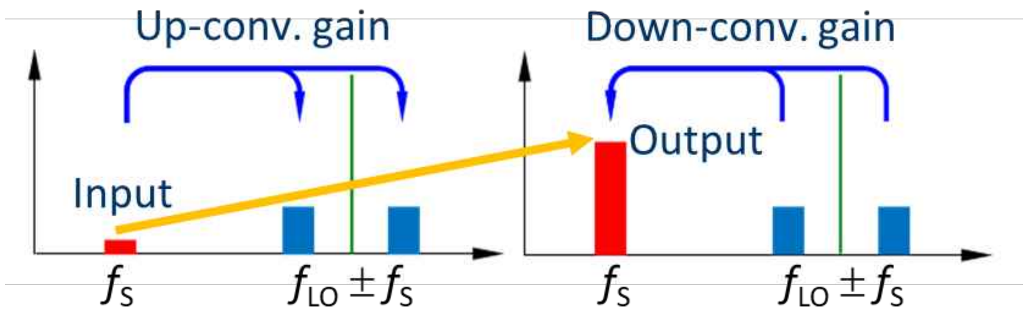
Semiconductor-based amplifier: 10 mW =>10 W(/1000 beams)

=> Low power consumption, low noise, broadband CLNA

SIS-mixer-based microwave amplifier

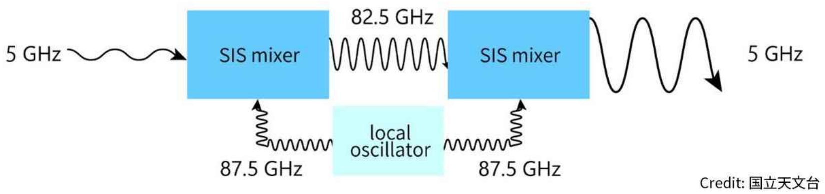
Y. Uzawa

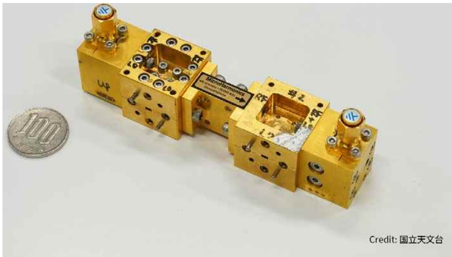


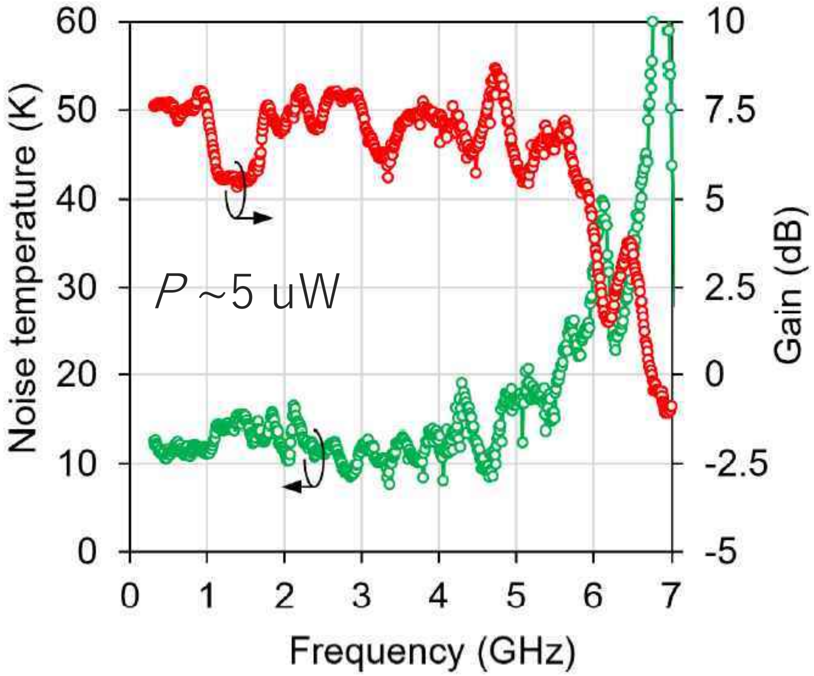


Y. Uzawa et al.,
J. Low Temp. Phys. **193**,
512 (2018).

T.-M. Shen et al.,
Appl. Phys. Lett. **36**,
777 (1980).





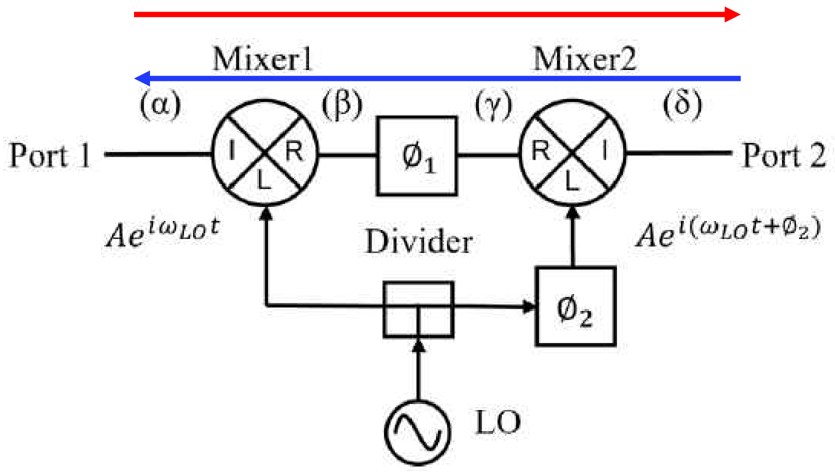


T. Kojima et al.,
Appl. Phys. Lett. **122**, 072601 (2023).

https://atc.mtk.nao.ac.jp/news/20230320/

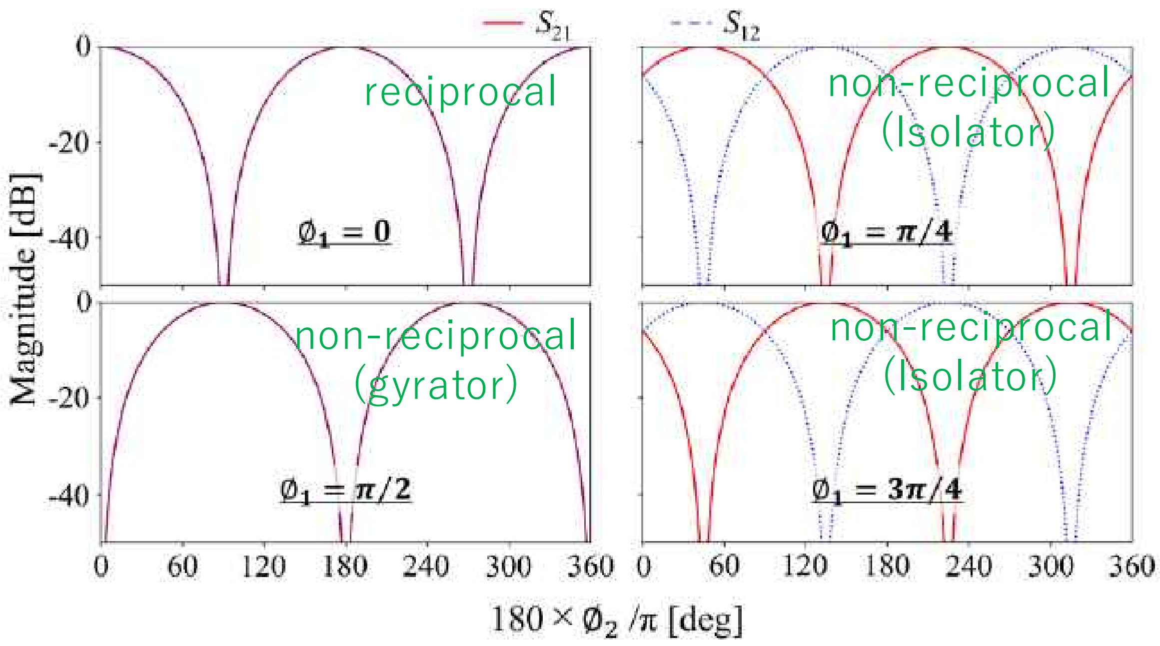
mixer-based non-reciprocity

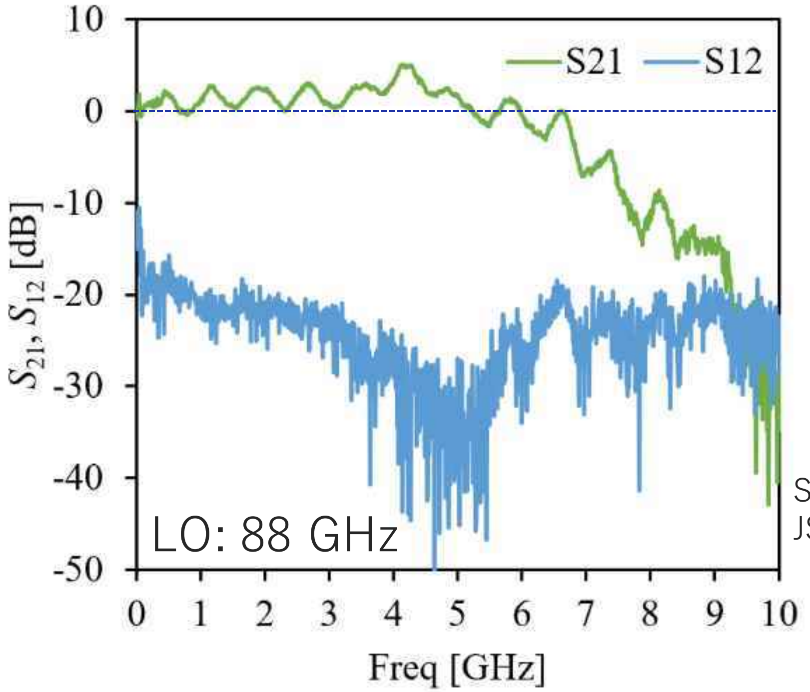
S. Masui et al., IEEE Microw. Wirel. Technol. Lett. **33**, 1051 (2023).



$$S_{21} = G_{\mathrm{USB}} e^{\mathrm{j}(\phi_1 - \phi_2)} + G_{\mathrm{LSB}} e^{-\mathrm{j}(\phi_1 - \phi_2)}$$

$$S_{12} = \underbrace{G_{\mathrm{USB}} e^{\mathrm{j}(\phi_1 + \phi_2)}}_{\text{upper sideband}} + \underbrace{G_{\mathrm{LSB}} e^{-\mathrm{j}(\phi_1 + \phi_2)}}_{\text{lower sideband}}$$



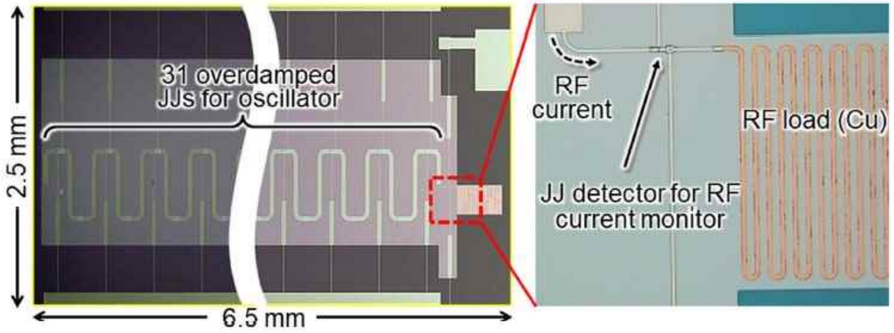


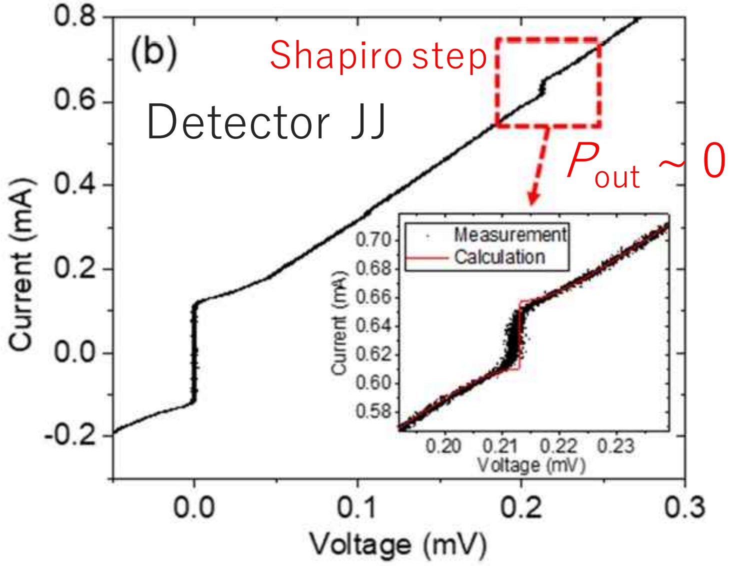
S. Masui et al.,
JSAP meeting 2023 spring

Josephson oscillator for LO source

A. Kawakami

100 GHz Josephson array oscillator with a detector JJ





P_{out} ~ 0.2 μW@100 GHz

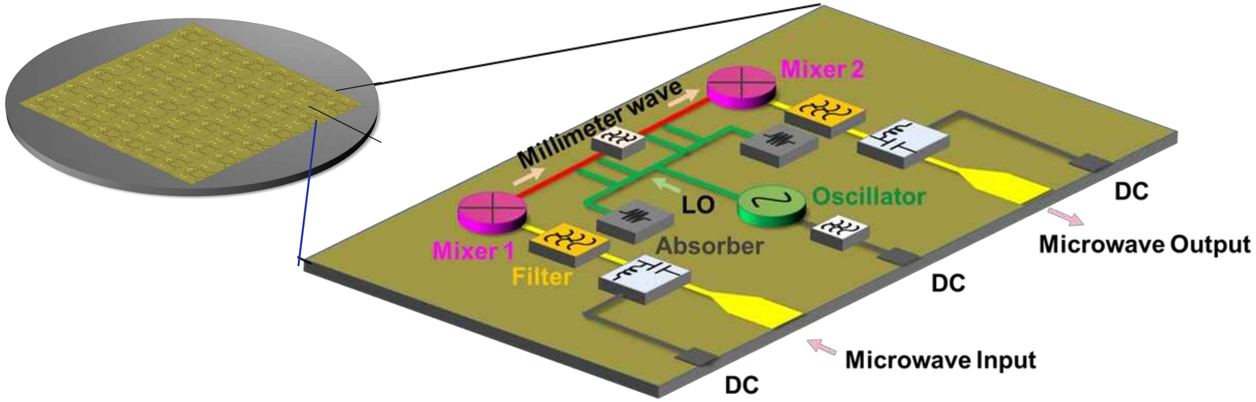
Y. Uzawa et al., IEEE Trans. Appl. Supercond. **33**, 1500804 (2023).

Our goal:

SIS-mixer based amplifier
+
Josephson oscillator

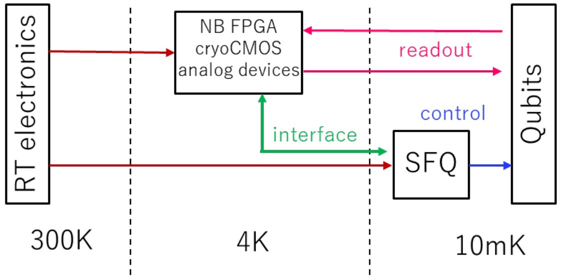
} monolithic chip

low power (~ uW)
directional gain
only dc power supply



Plans for the second half of the project

Plans for the second half of the project

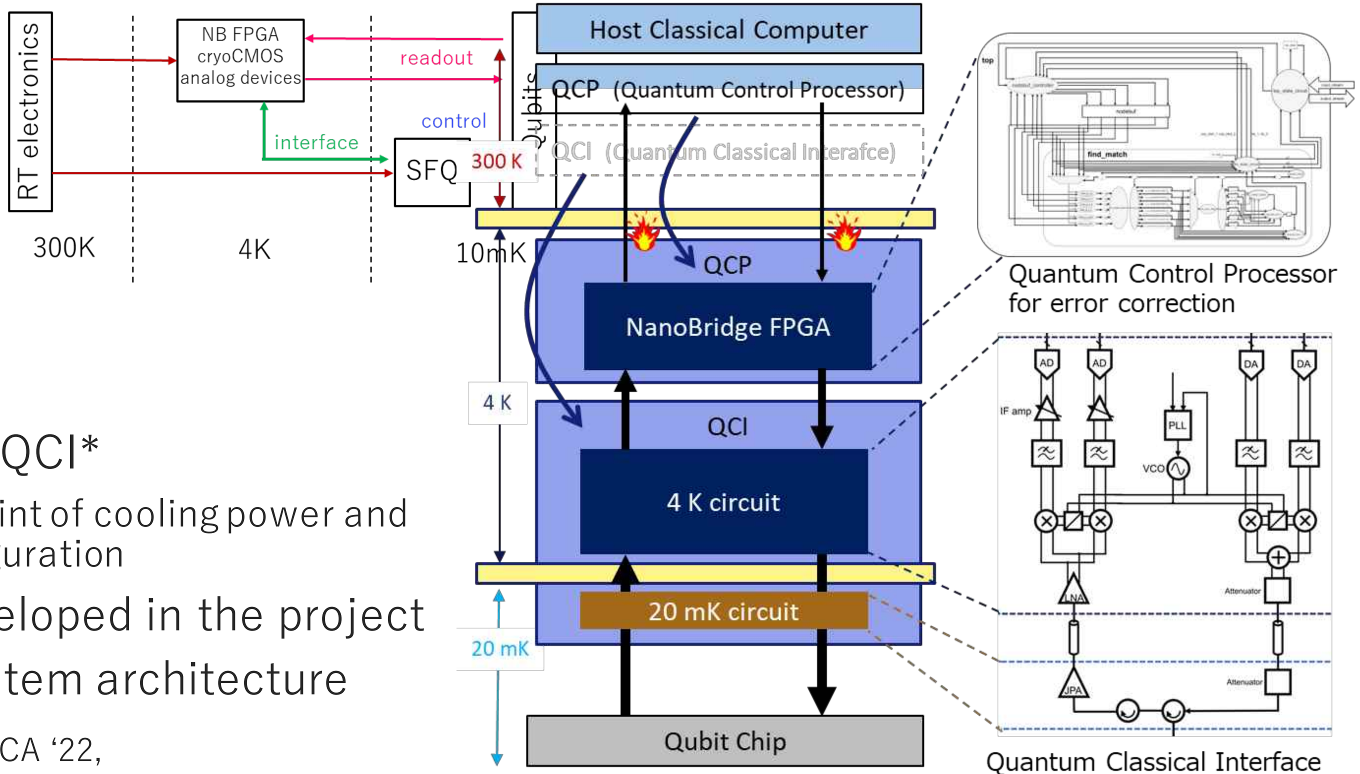


K. Inoue

Development of cryo-electronics

- construction of standard cell libraries
  - ✓ low j_c SFQ circuits for 10 mK operation
  - ✓ digital and analog CMOS circuits for 4 K operation

System-Level Architecture Exploration



- operation test of functional circuits
  - test of individual circuits
  - demonstration of qubit control/readout
  - interface between cryo-electronics

- System-level architecture exploration
  - Develop an evaluation environment of QCP + QCI*
    - e.g. evaluate maximum # of qubits under the constraint of cooling power and required logical error rate for a given hardware configuration
  - Evaluate the impact of core technologies developed in the project
  - Propose future direction of in-refrigerator system architecture

* I. Byun et al., Proceedings of ISCA '22,
D. Min et al., Proceedings of ISCA '23.

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\Orchestrating a brighter world

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